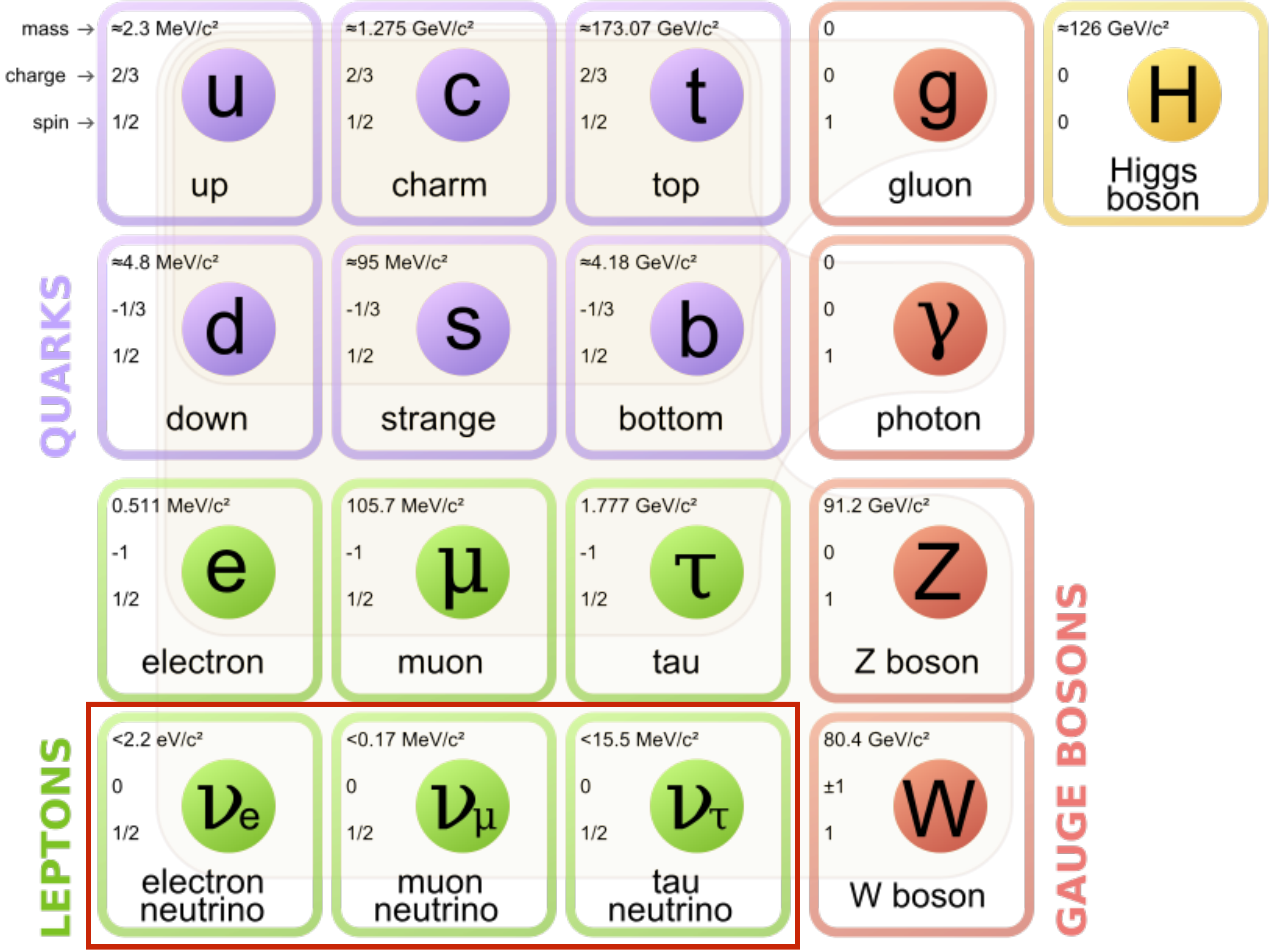
Latest Oscillation Results from NOvA

Alexander Radovic

College of William and Mary

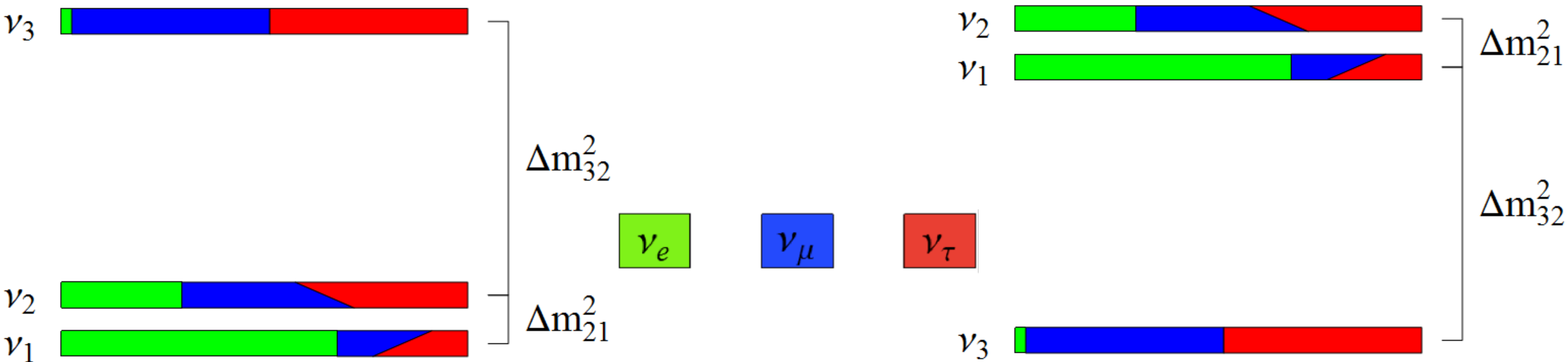
Neutrino Oscillations



Neutrino Oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U^* \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U^*_{\beta j} e^{-i \frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$



Why Study Neutrino Oscillations?

Neutrino oscillations raised as many questions as it answered:

- Why is lepton sector mixing much larger than quark sector mixing? Is θ_{23} maximal?
- What is the hierarchy of neutrino masses?
- Is there CP violation in the lepton sector?

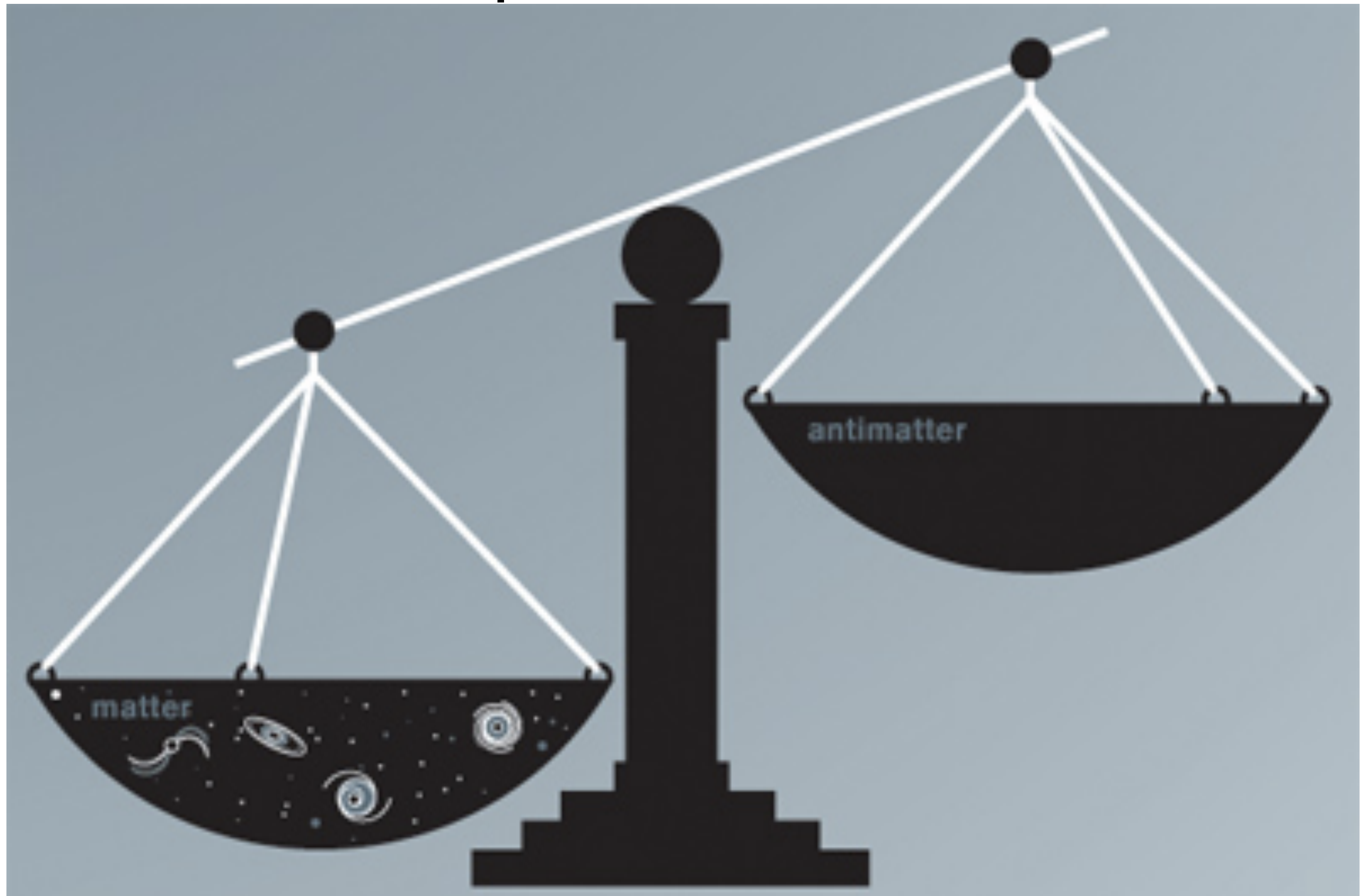
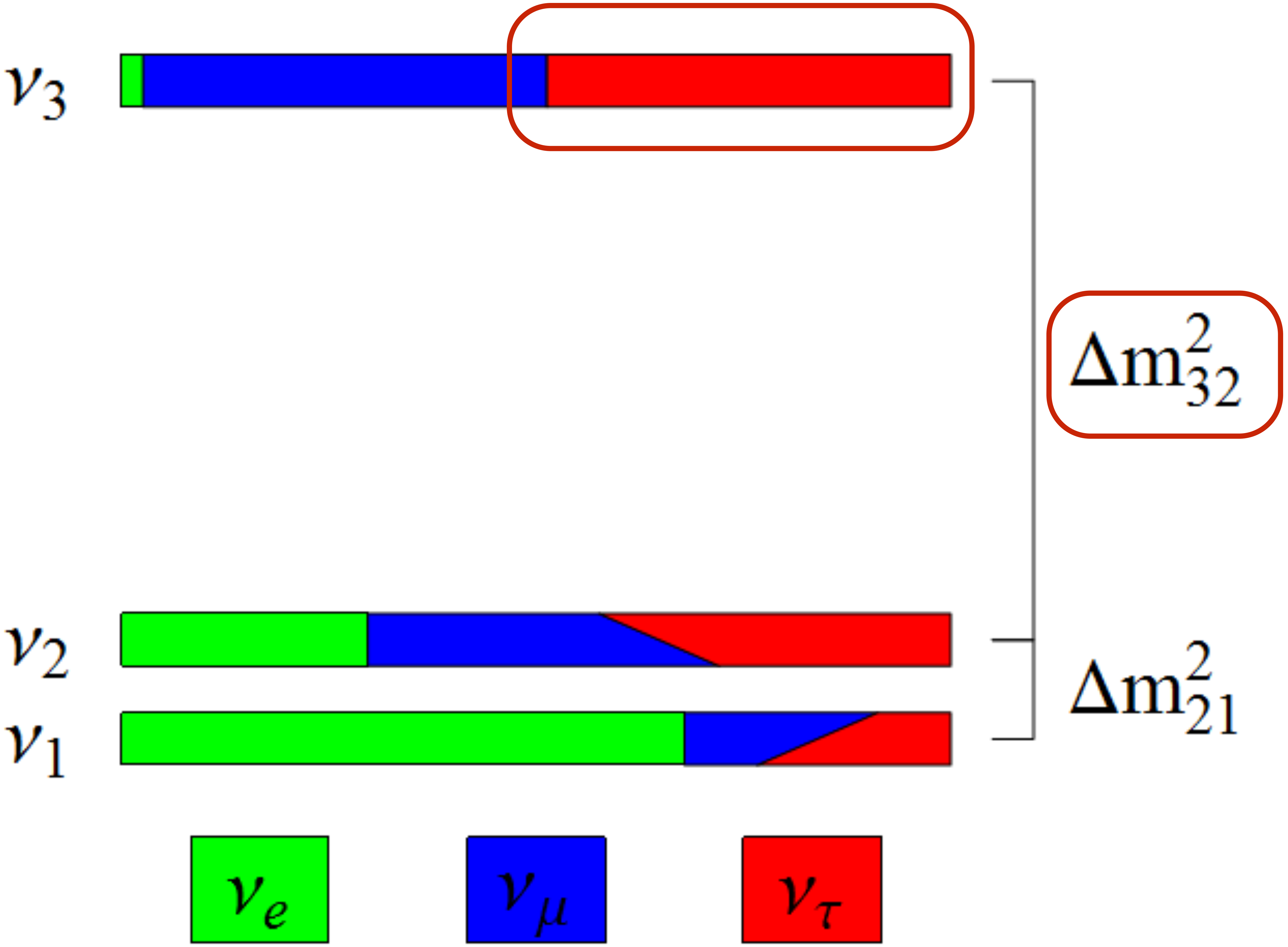


Illustration: Sandbox Studio via symmetry magazine

NOvA Physics Goals

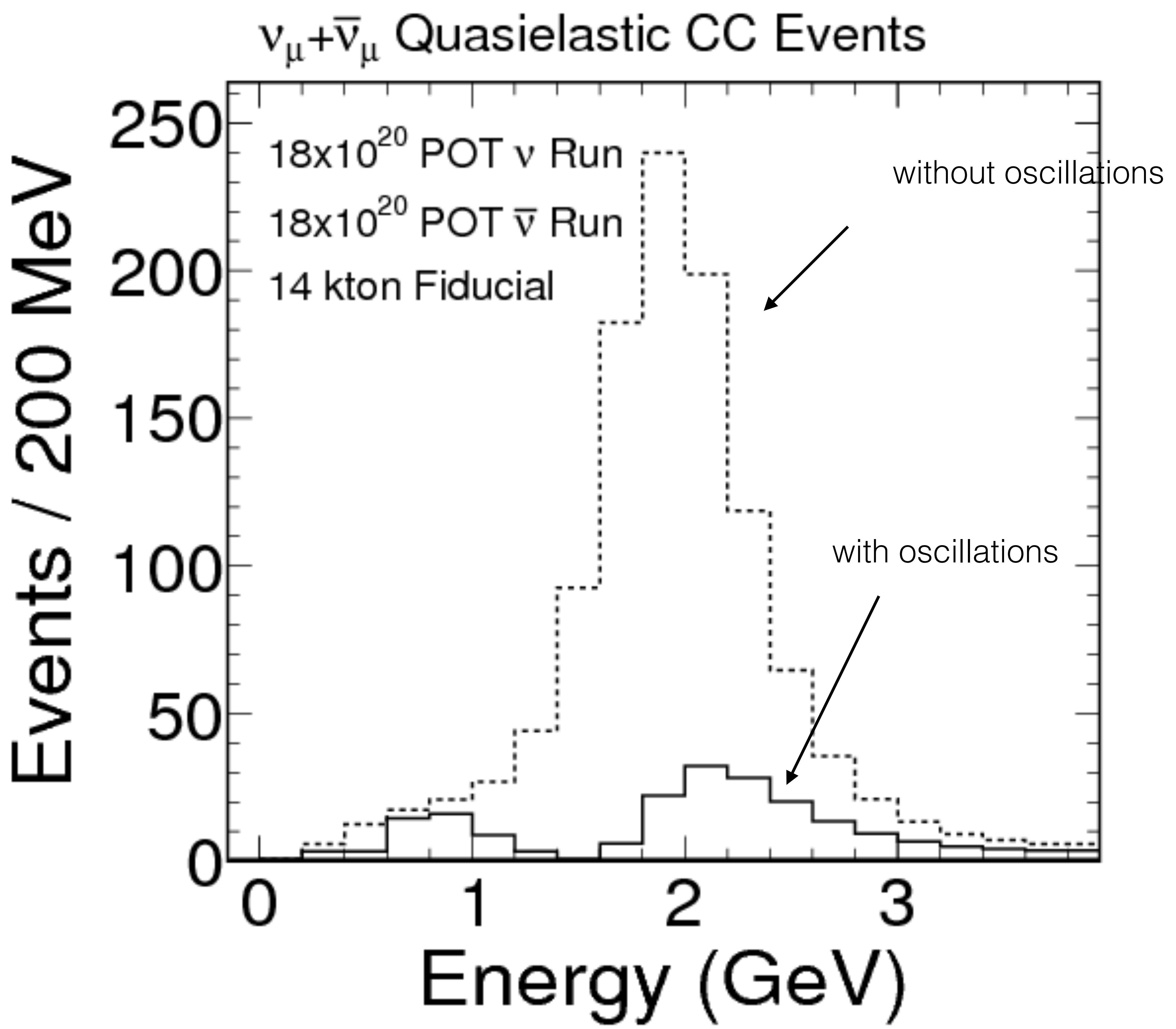


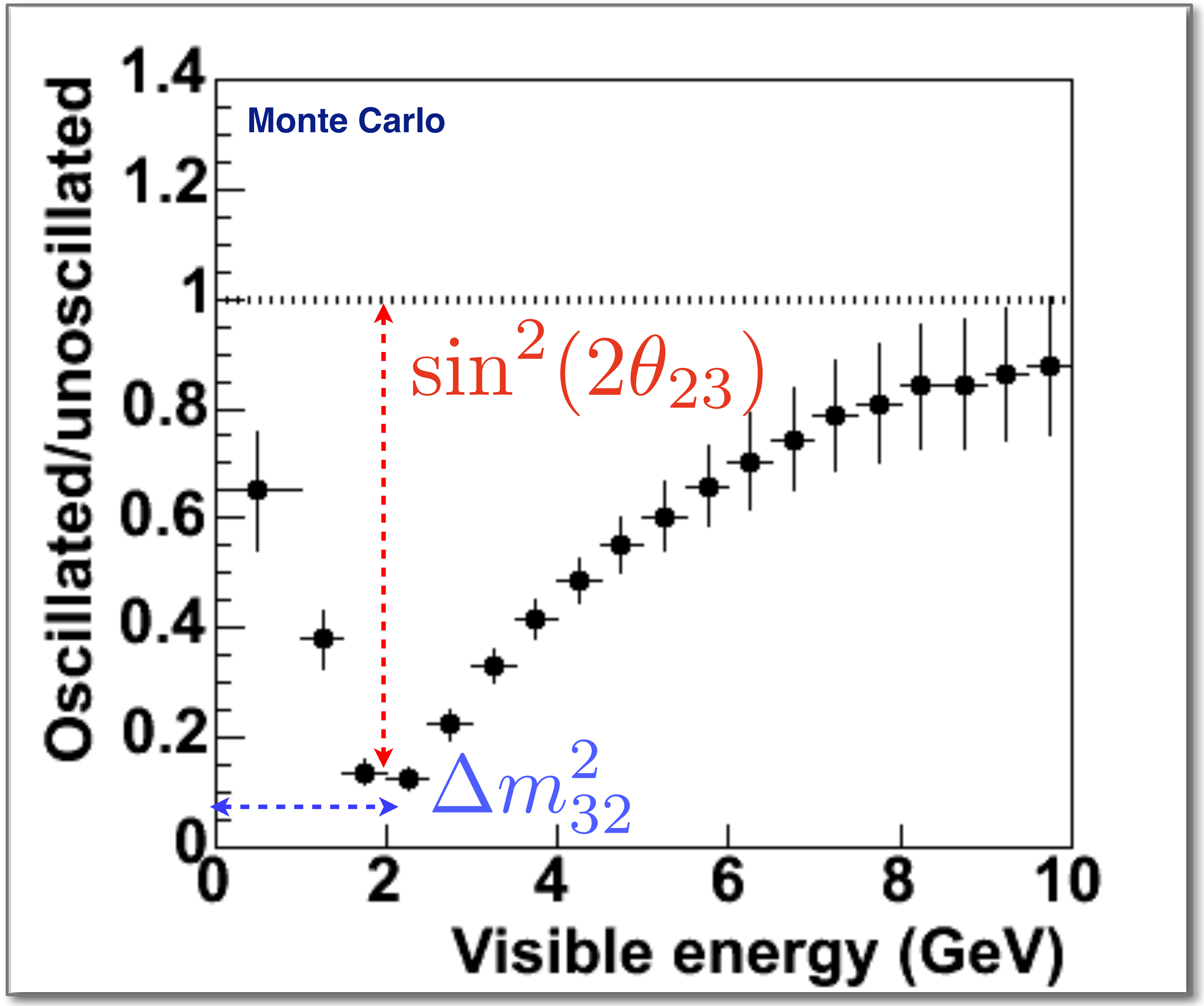
Precise measurements:
Δm^2_{32} and $\sin^2(2\theta_{23})$ for neutrinos and antineutrinos

Strong Constraints on:
θ_{23} octant
δ_{cp}
mass hierarchy

ν_μ Disappearance

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27\Delta m^2_{atm} L}{E}\right)$$





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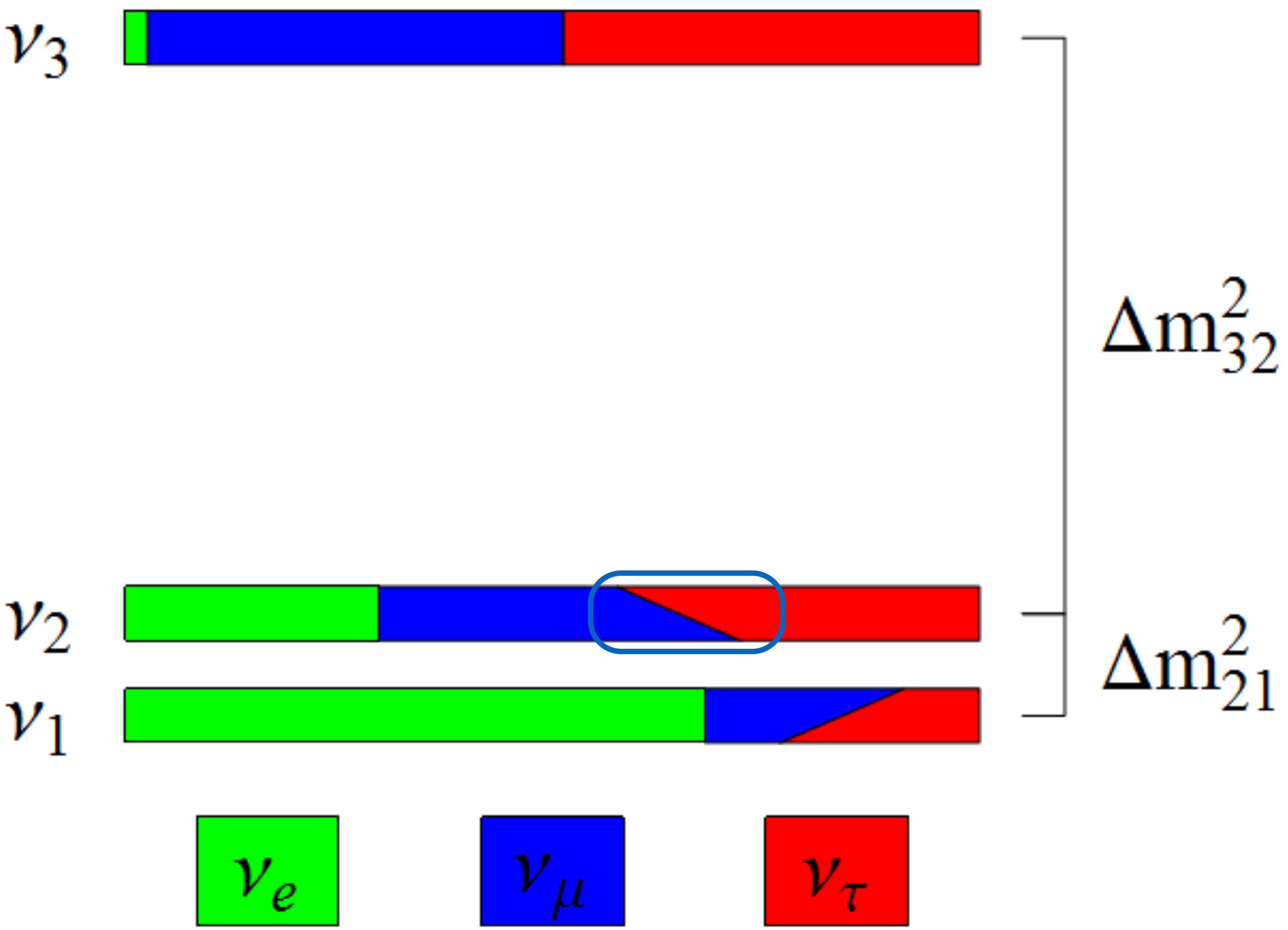

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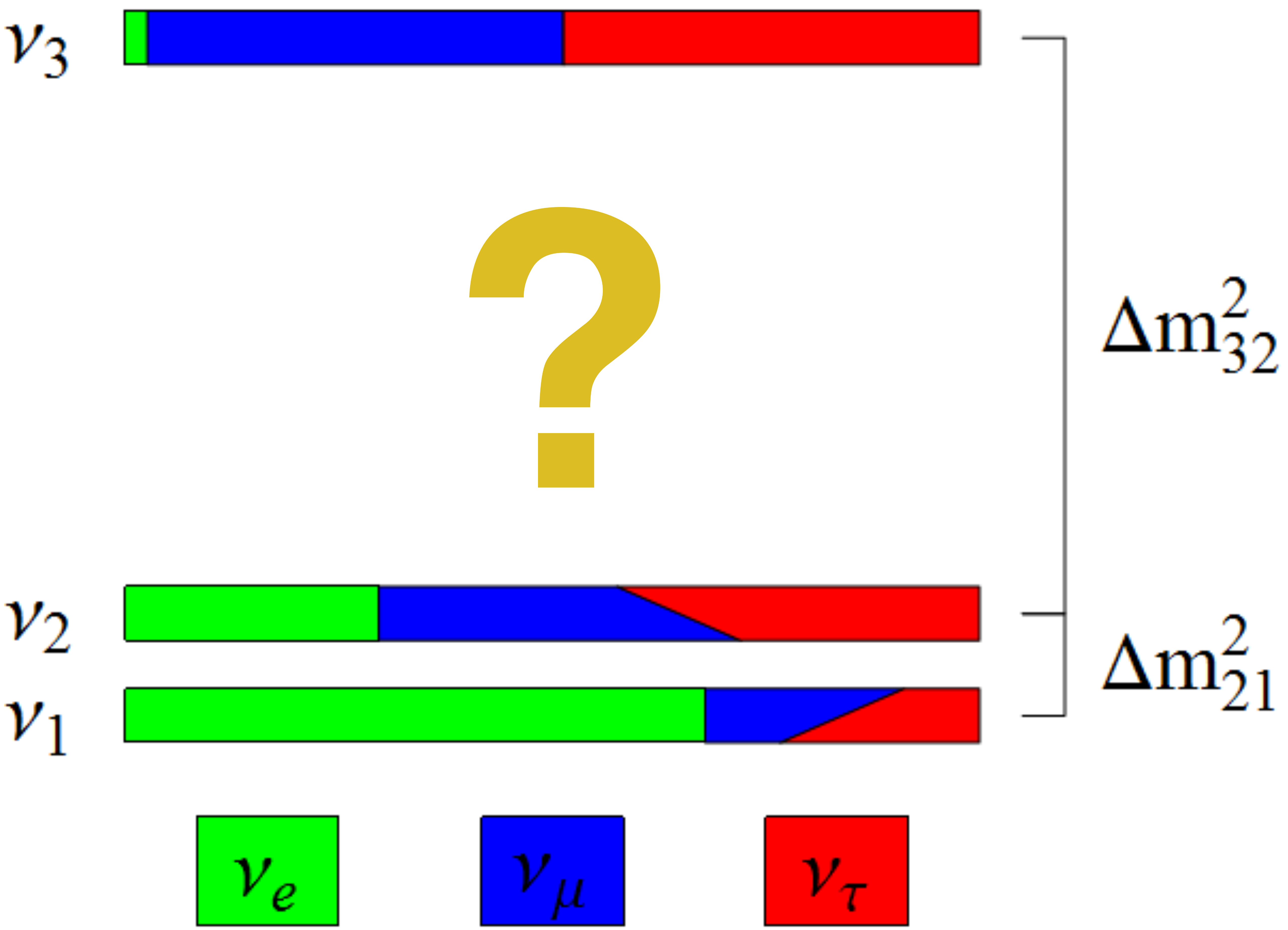

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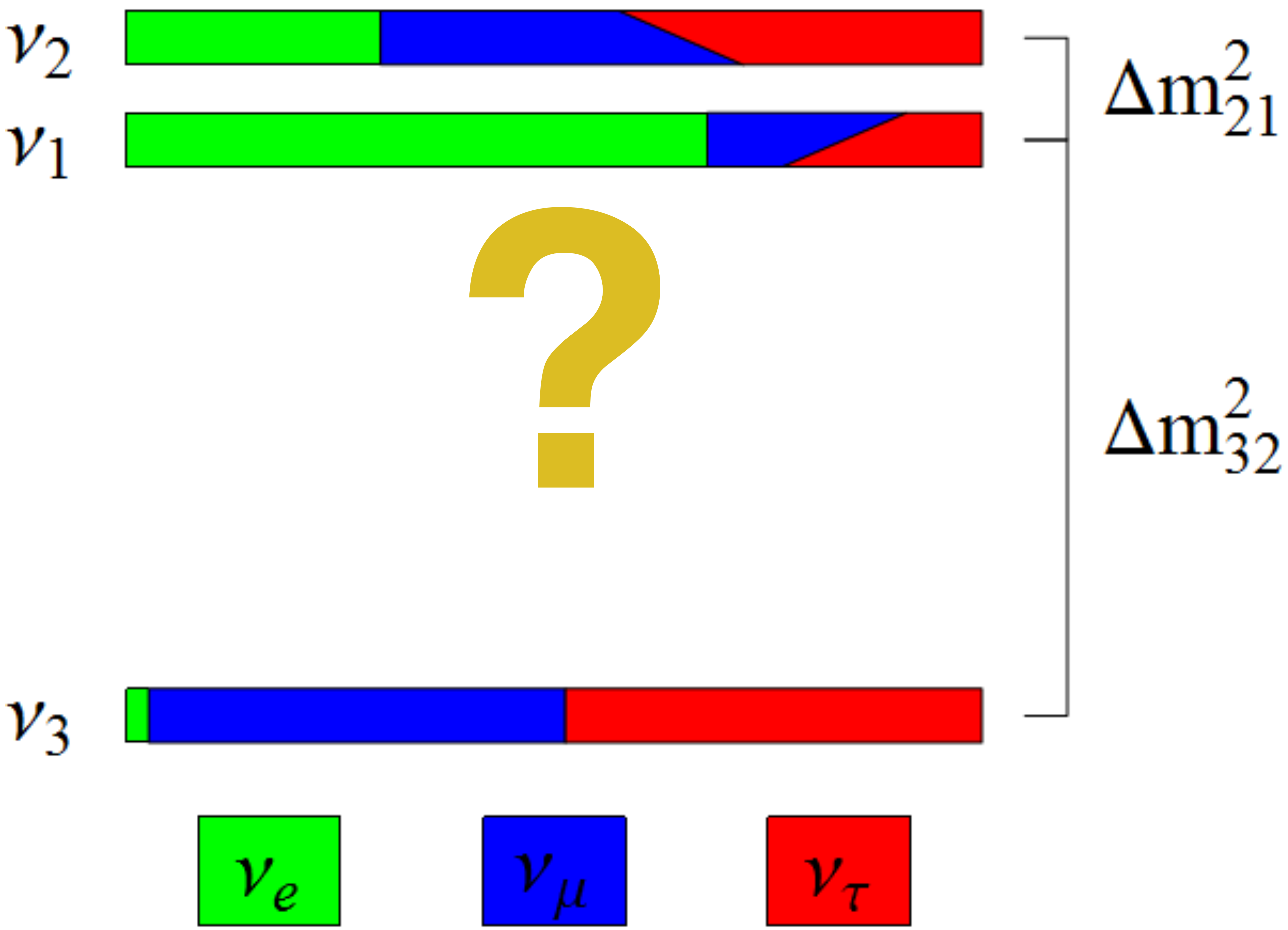

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Δm^2_{32} and $\sin^2(2\theta_{23})$ for neutrinos and antineutrinos

Strong Constraints on:
θ_{23} octant
δ_{cp}
mass hierarchy

ν_e Appearance

By measuring beam muon neutrinos which have oscillated to electron neutrinos we gain the power to constrain:

θ_{23} octant

δ_{cp}

mass hierarchy

$$P(\nu_\mu \to \nu_e) \approx \left| \sqrt{P_{atm}} e^{-i\left(\frac{\Delta m^2_{32} L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

Solar term contributes <1% at ~400 L/E

ν_e Appearance

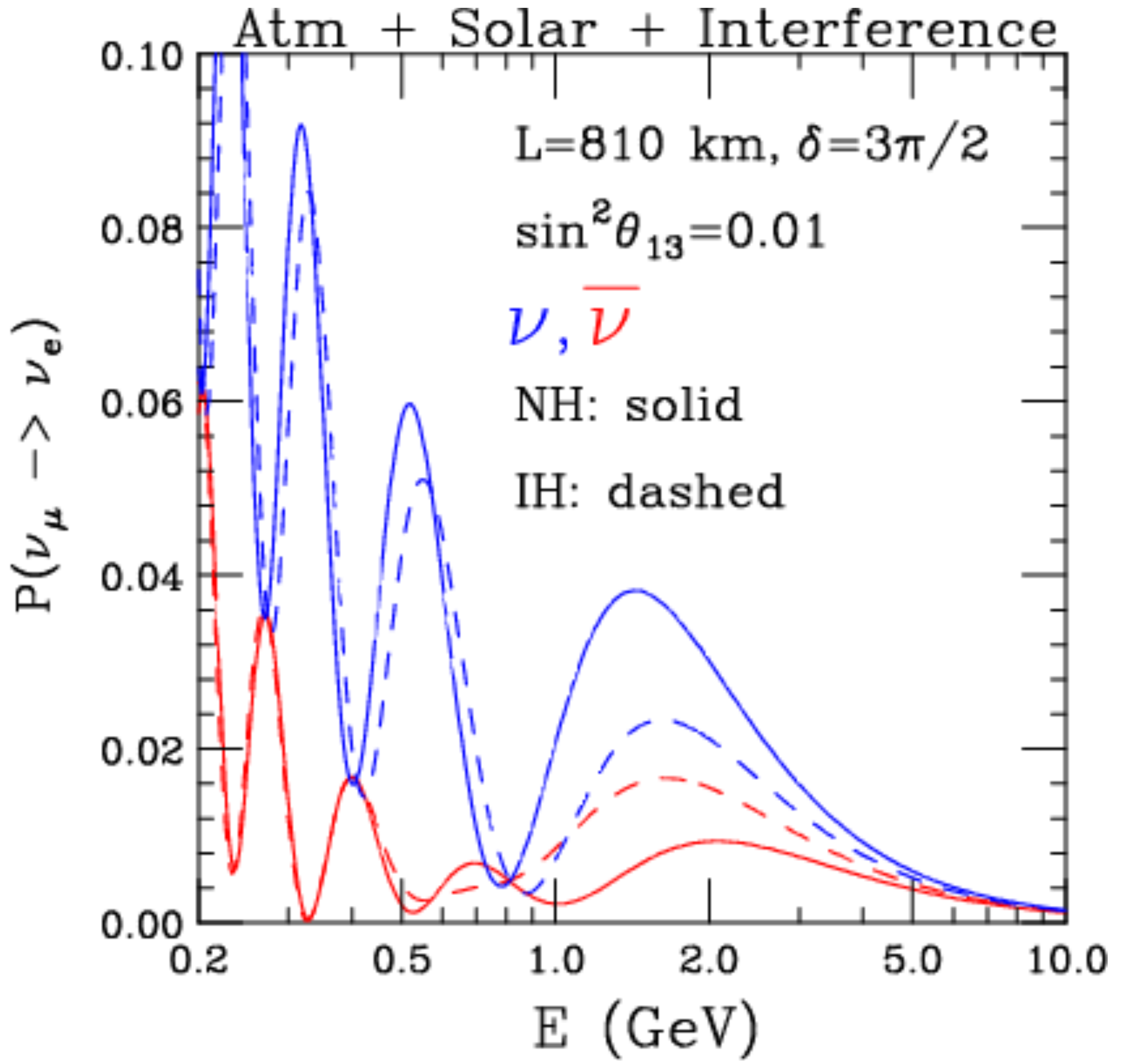
By measuring beam muon neutrinos which have oscillated to electron neutrinos we gain the power to constrain:

θ_{23} octant

δ_{cp}

mass hierarchy

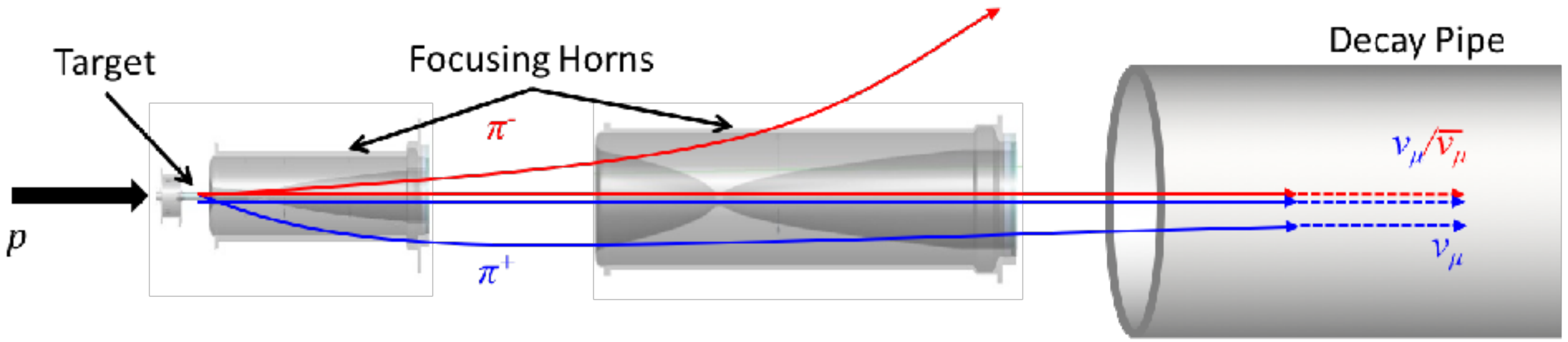
Electron neutrinos experience an extra interaction as they pass through matter, modifying oscillation probabilities, giving us a window into the mass hierarchy.

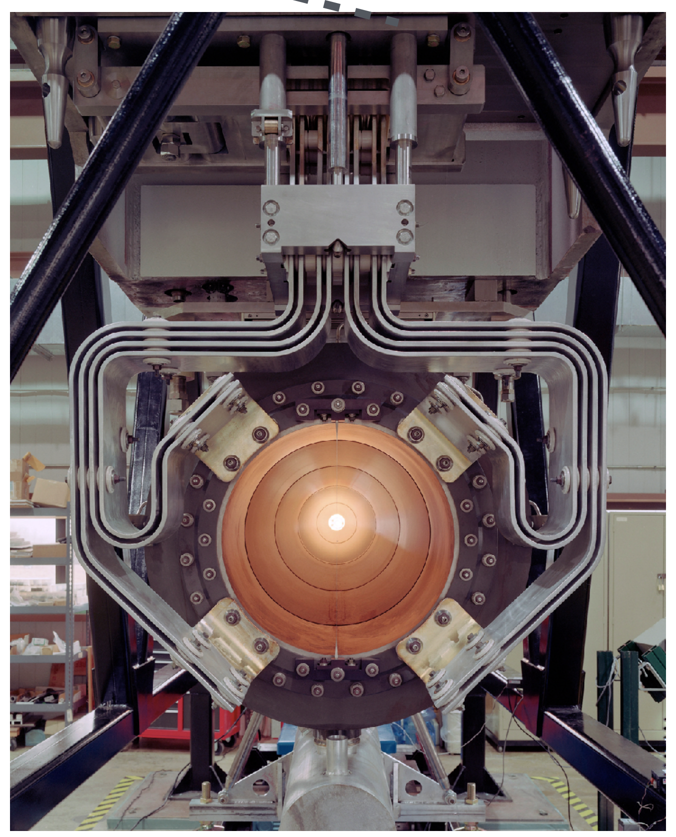


From S. Parke, "Neutrino Oscillation Phenomenology" in Neutrino Oscillations: Present Status and Future Plans

NuMI Off-axis ν_e Appearance

Studying oscillations over a 810km baseline with two functionally identical detectors and the worlds most powerful muon neutrino beam, NuMI.





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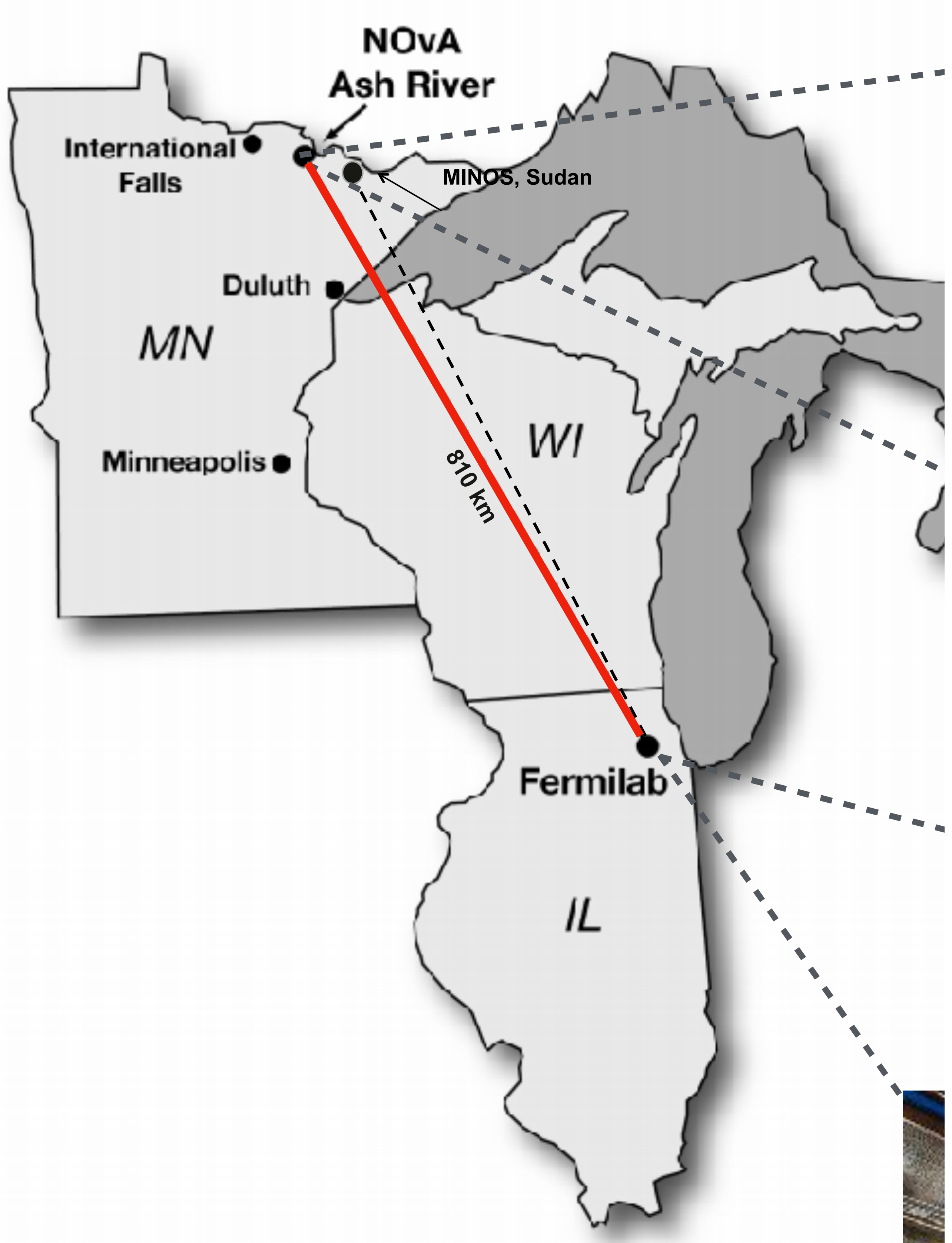
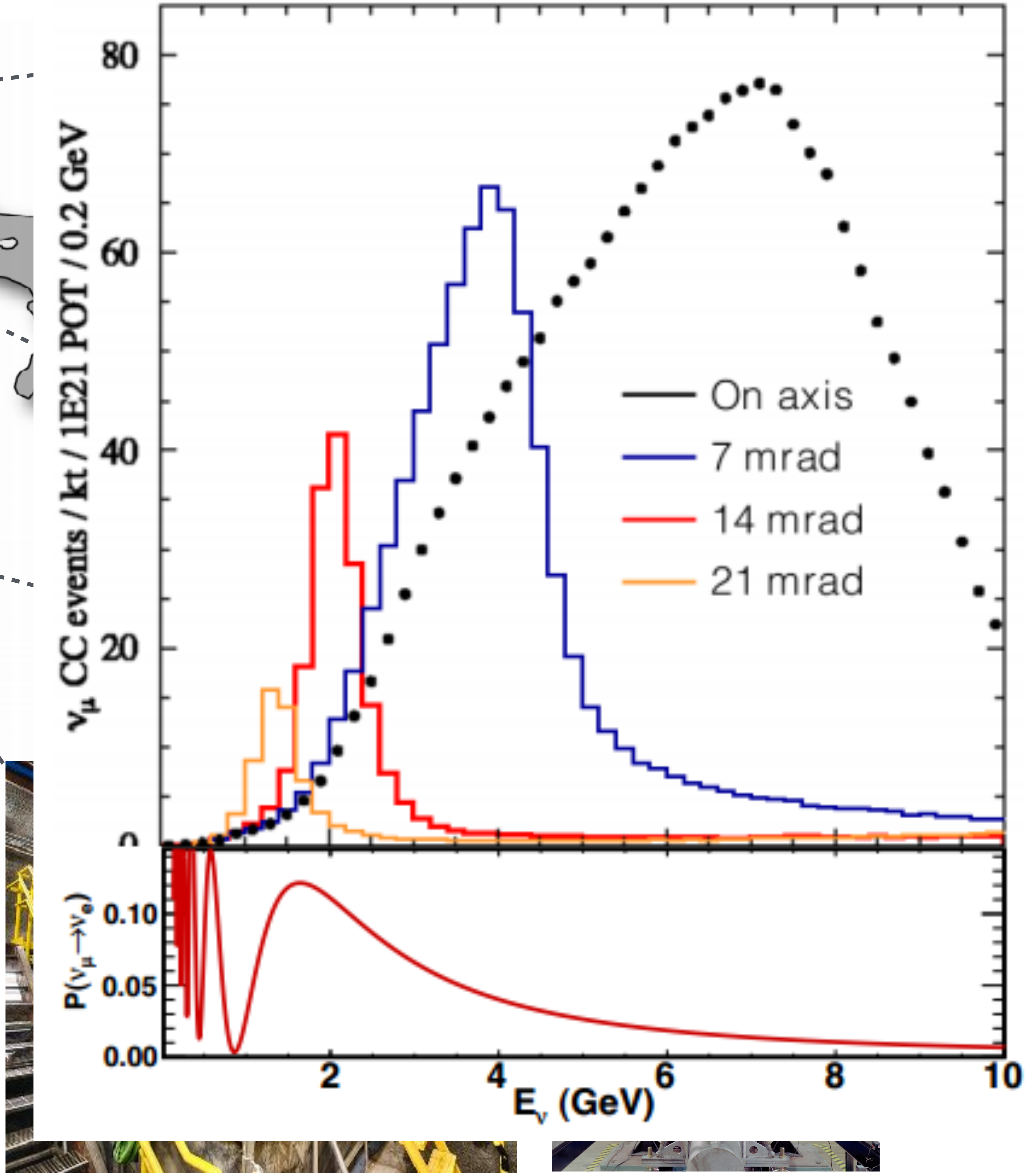
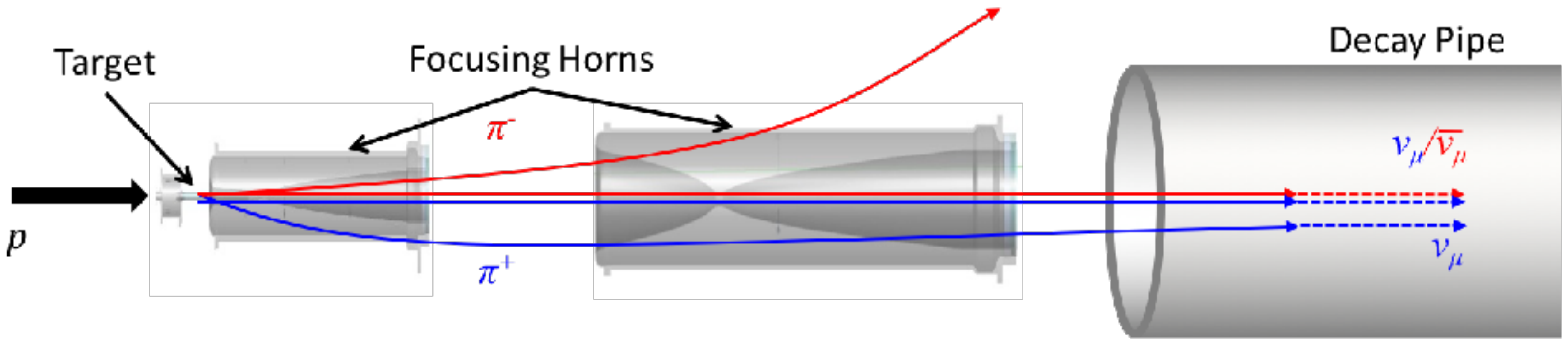
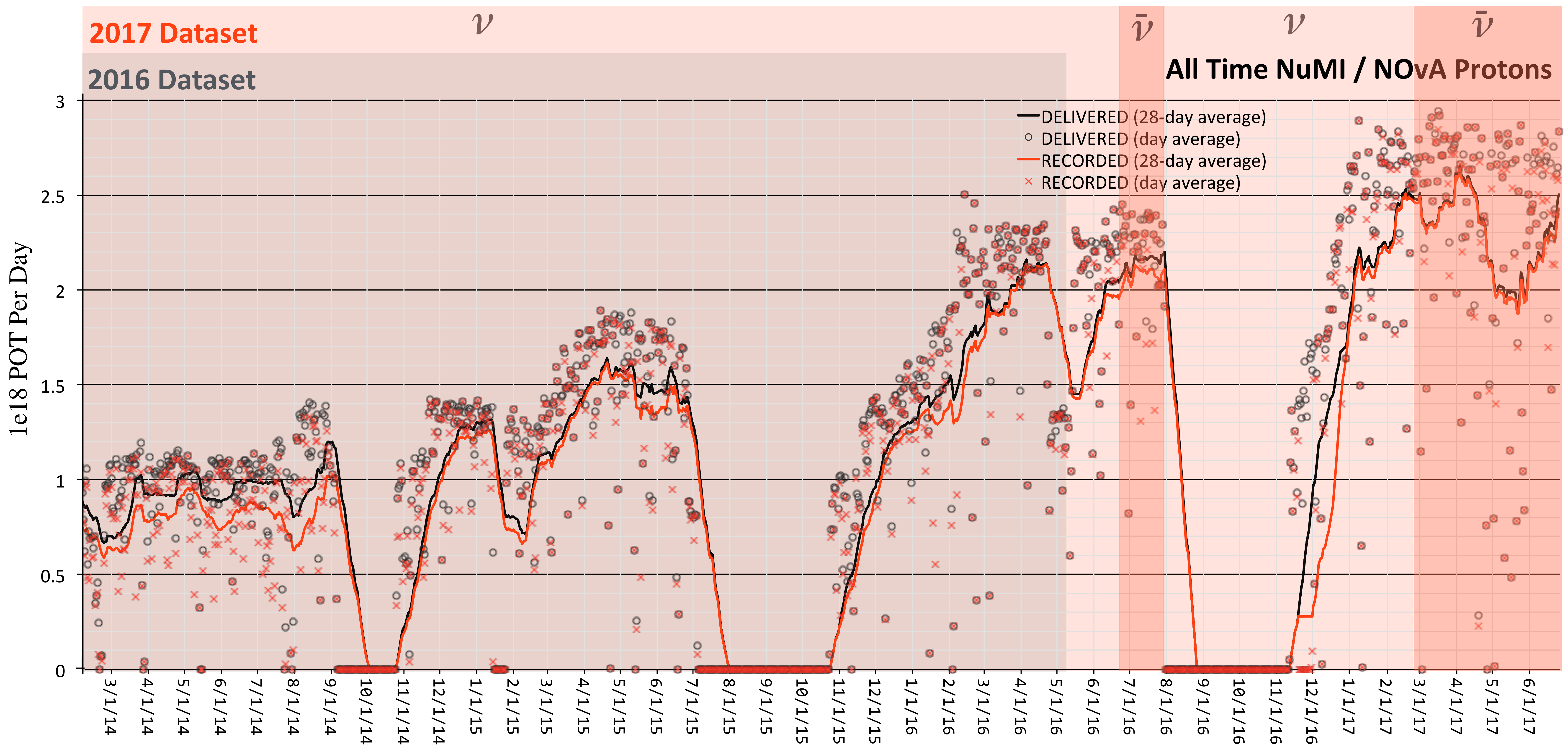




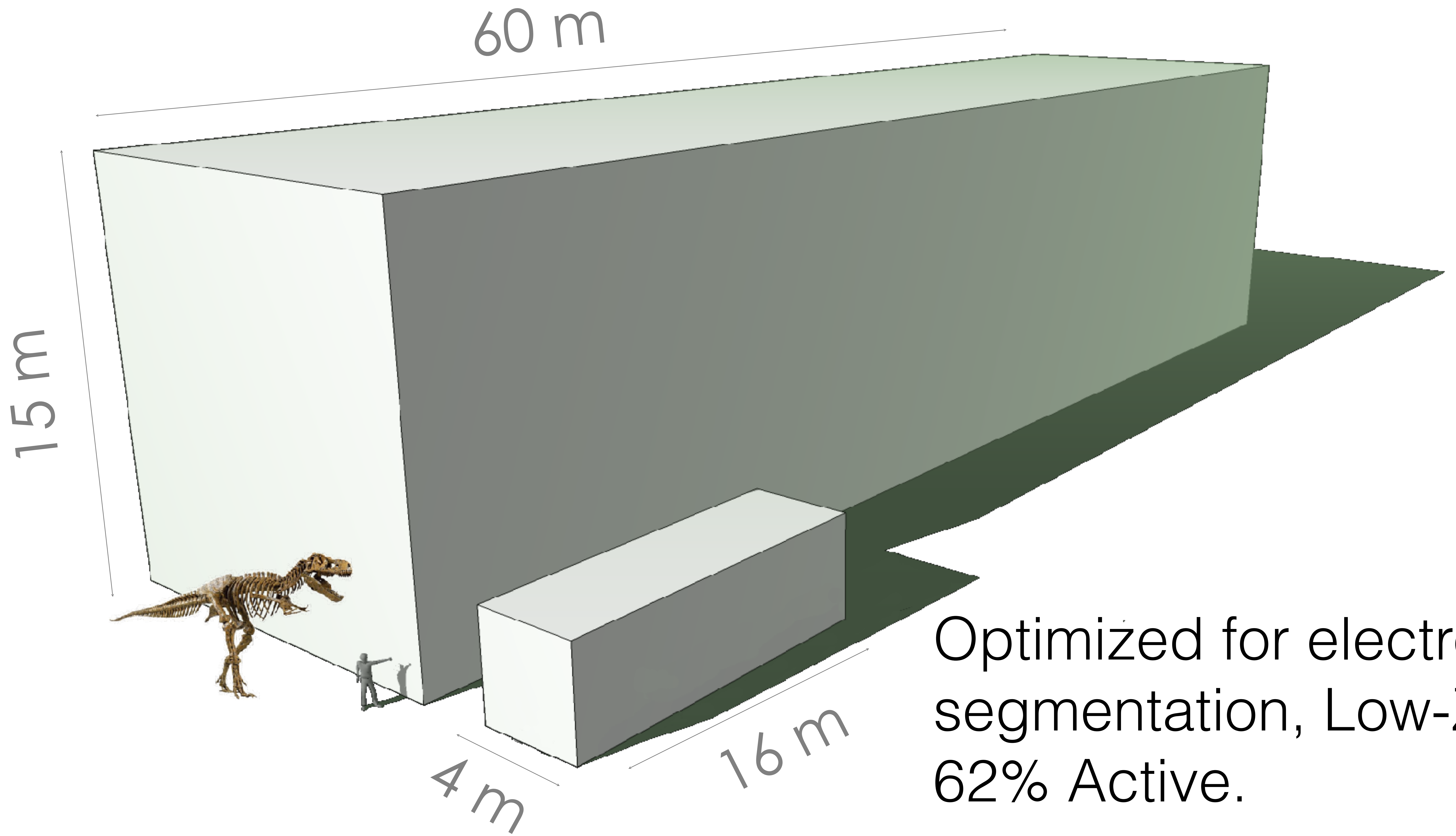


Beam Exposure

- 8.85×10^{20} POT in 14 kton equivalent detector
  - 50% more exposure than the 2016 analysis
- Currently running in anti-neutrino mode
- Running at 700 kW design goal since June 2016!

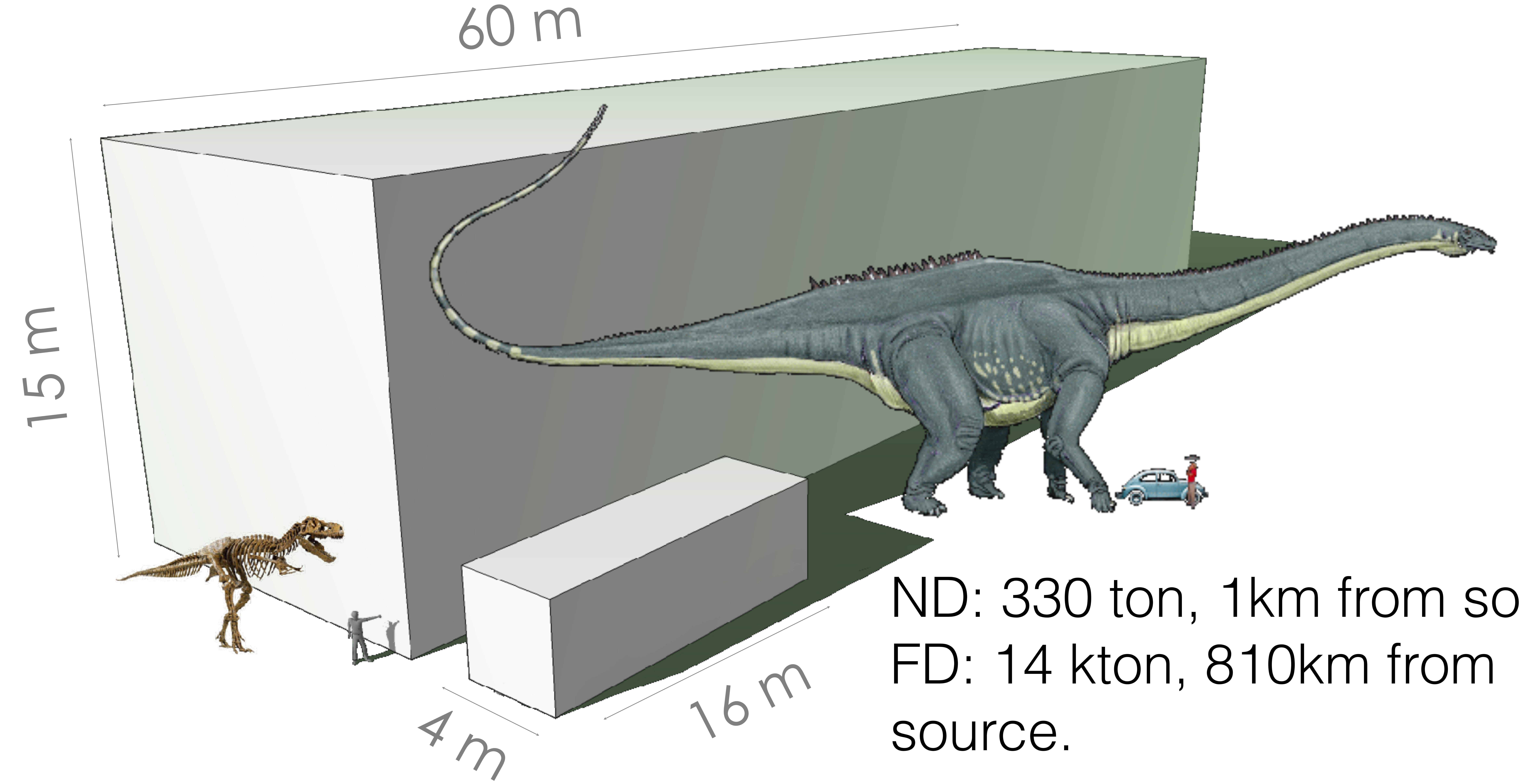


The NOvA Detectors



Optimized for electron ID, fine segmentation, Low-Z, and 62% Active.

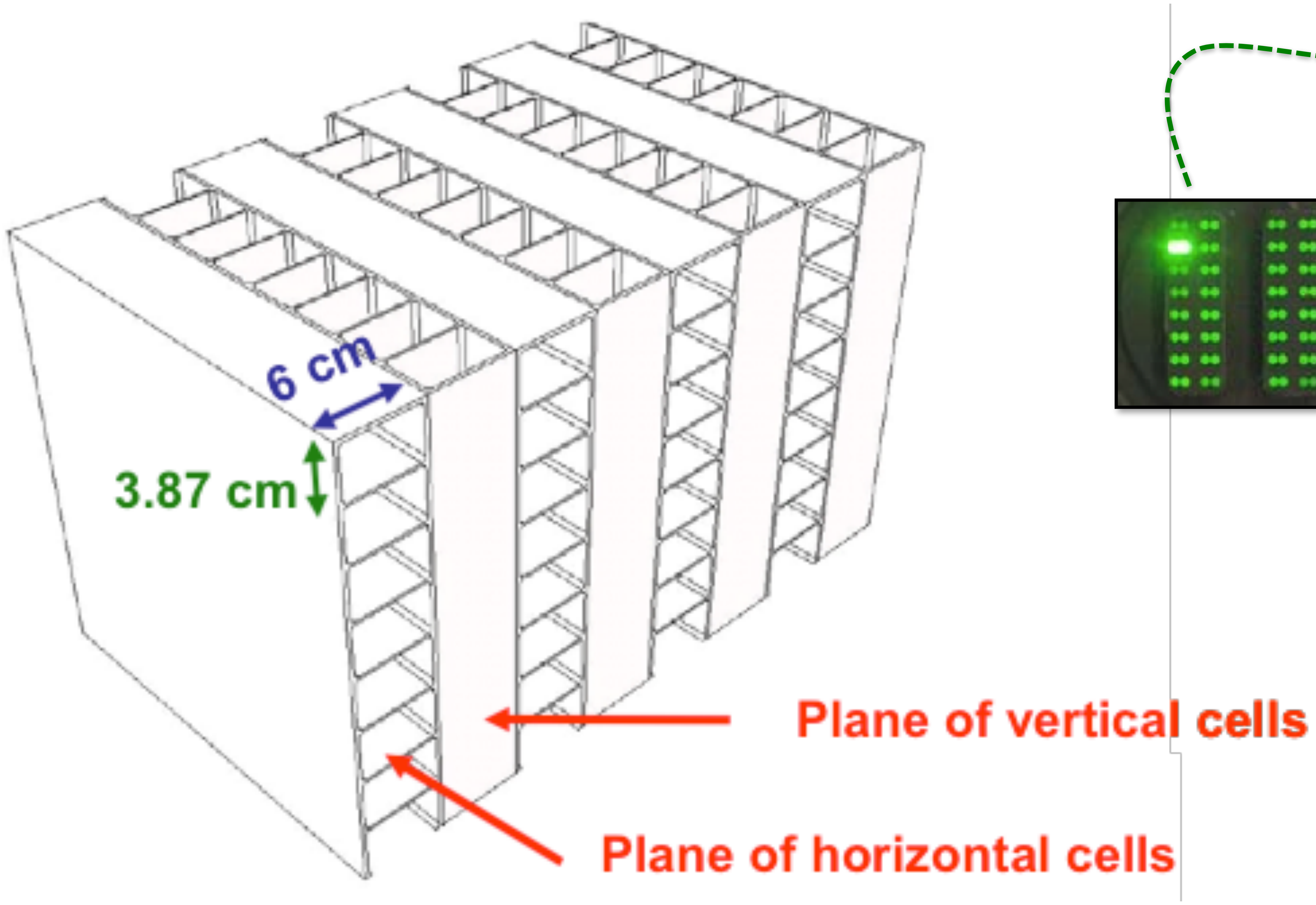
The NOvA Detectors

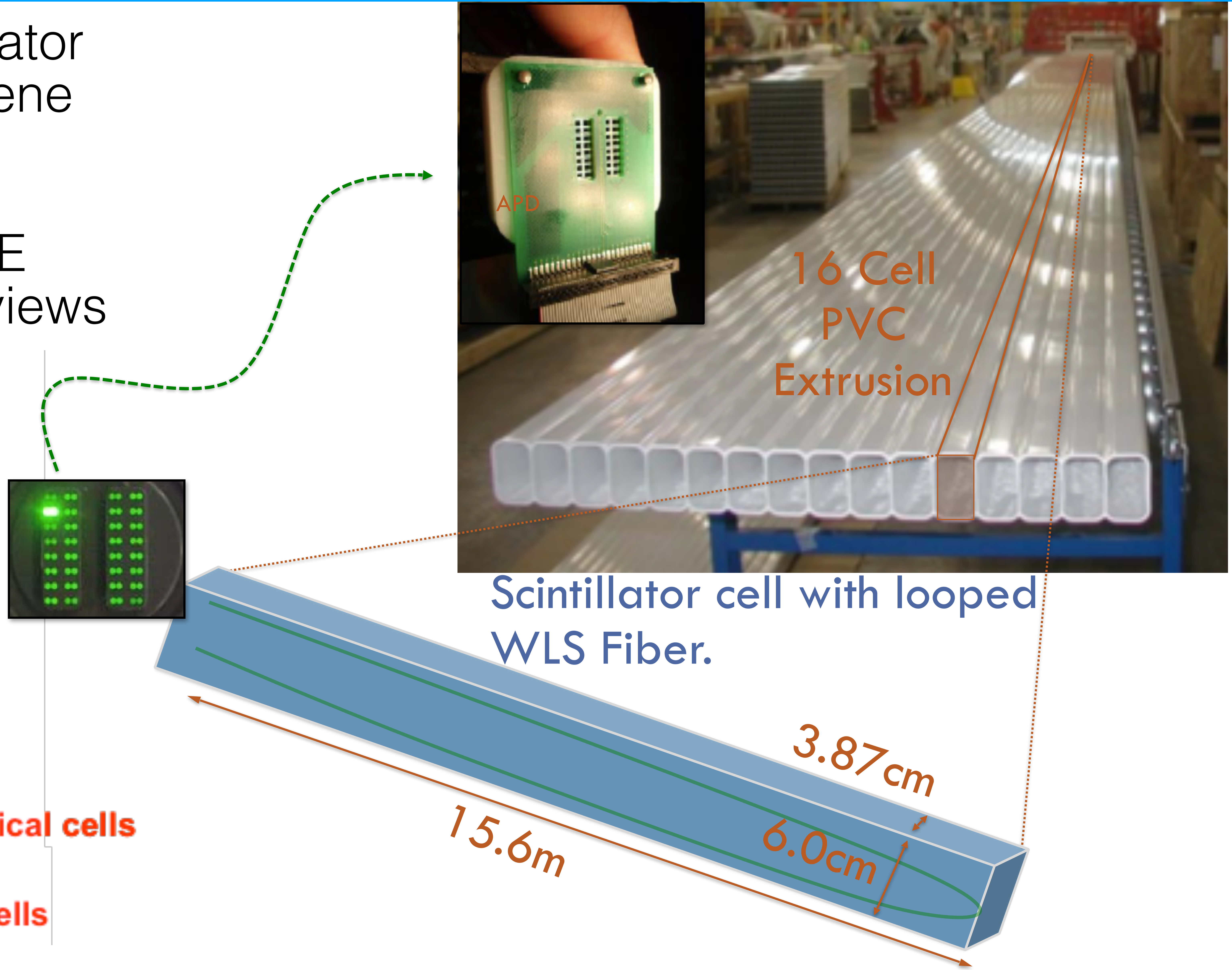


ND: 330 ton, 1km from source.
FD: 14 kton, 810km from source.

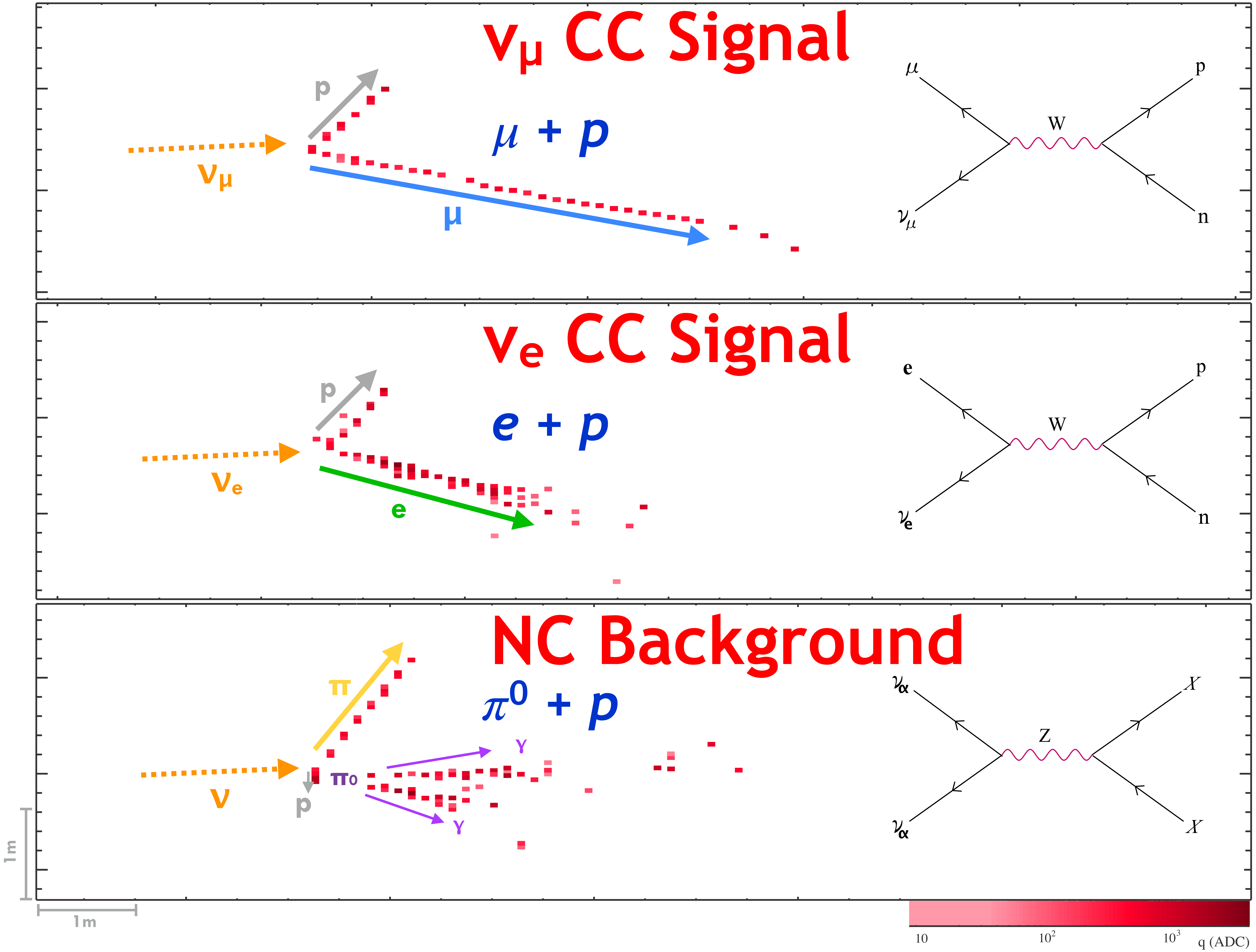
Detector Technology

- PVC extrusion + Liquid Scintillator
  - mineral oil + 5% pseudocumene
- Read out via WLS fiber to APD
  - FD has ~344,000 channels
  - muon crossing far end ~40 PE
- Layered planes of orthogonal views





NOvA Event Topologies



1 radiation length = 38cm (6 cell depths, 10 cell widths)

What's New?

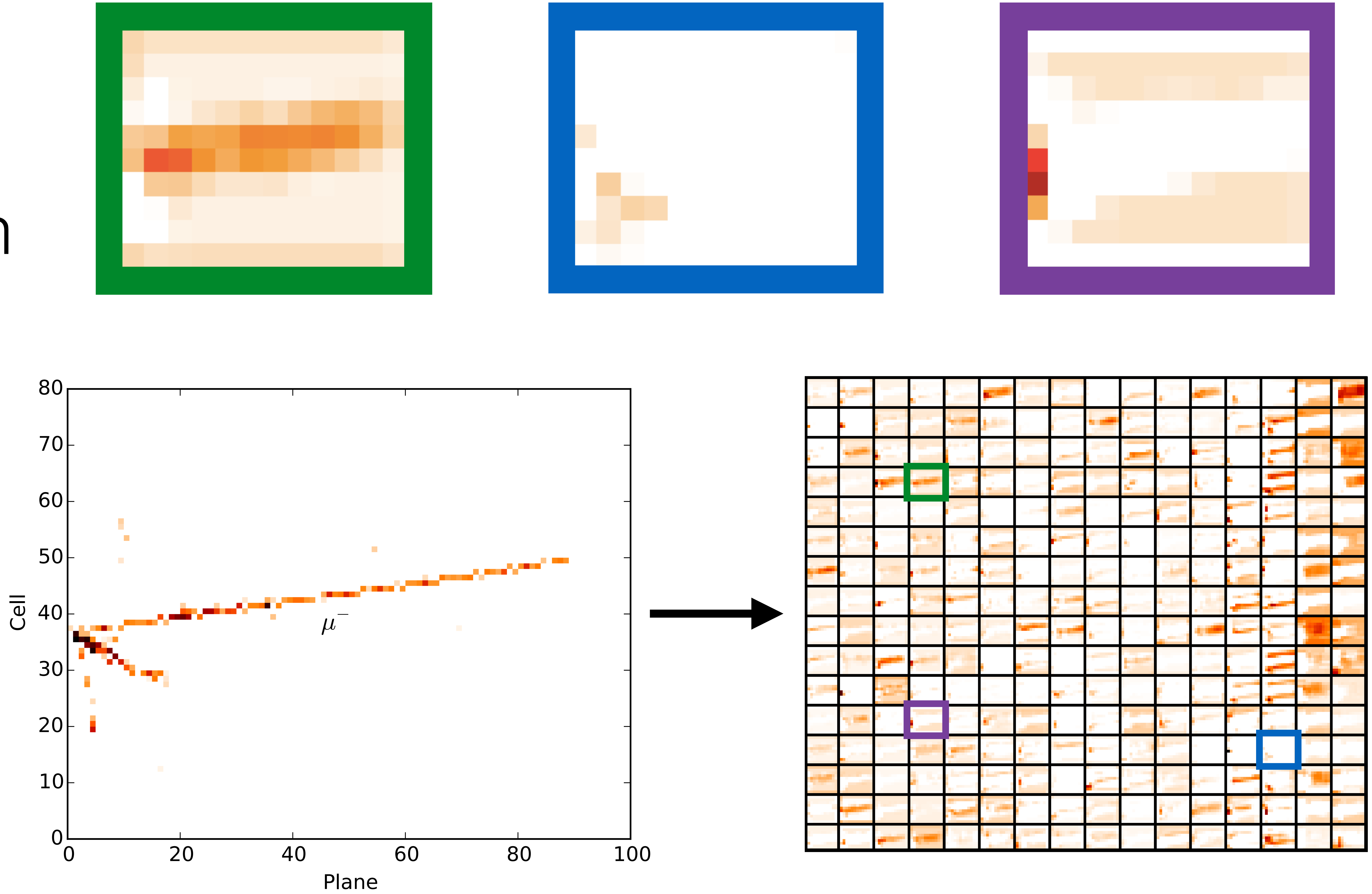
- **More data,** 50% more than our last oscillation update.
- **Improved analysis,** continued use of deep learning tools for our appearance and now also for our disappearance measurements. Binning in energy resolution that better exploits the information in the existing data.
- **Retuned cross section modeling,** continued development of how we treat cross sections including crucial multi-nucleon effects.
- **Detector simulation improvements,** dramatically reducing some of our largest uncertainties in previous measurements.
- **Data driven flux estimates,** developed by MINERvA.

Deep Learning Inspired PID: ν_e & ν_μ Selection

A. Radovic, JETP January 2018

Previously only used for our ν_e analysis, now our ν_μ analysis also features the same event selection technique based on ideas from computer vision and deep learning.

Additionally now used to reclaim a new class of previously rejected ν_e events.



"A Convolutional Neural Network Neutrino Event Classifier"
A. Aurisano, A. Radovic, and D. Rocco et al
Journal of Instrumentation, Volume 11, September 2016

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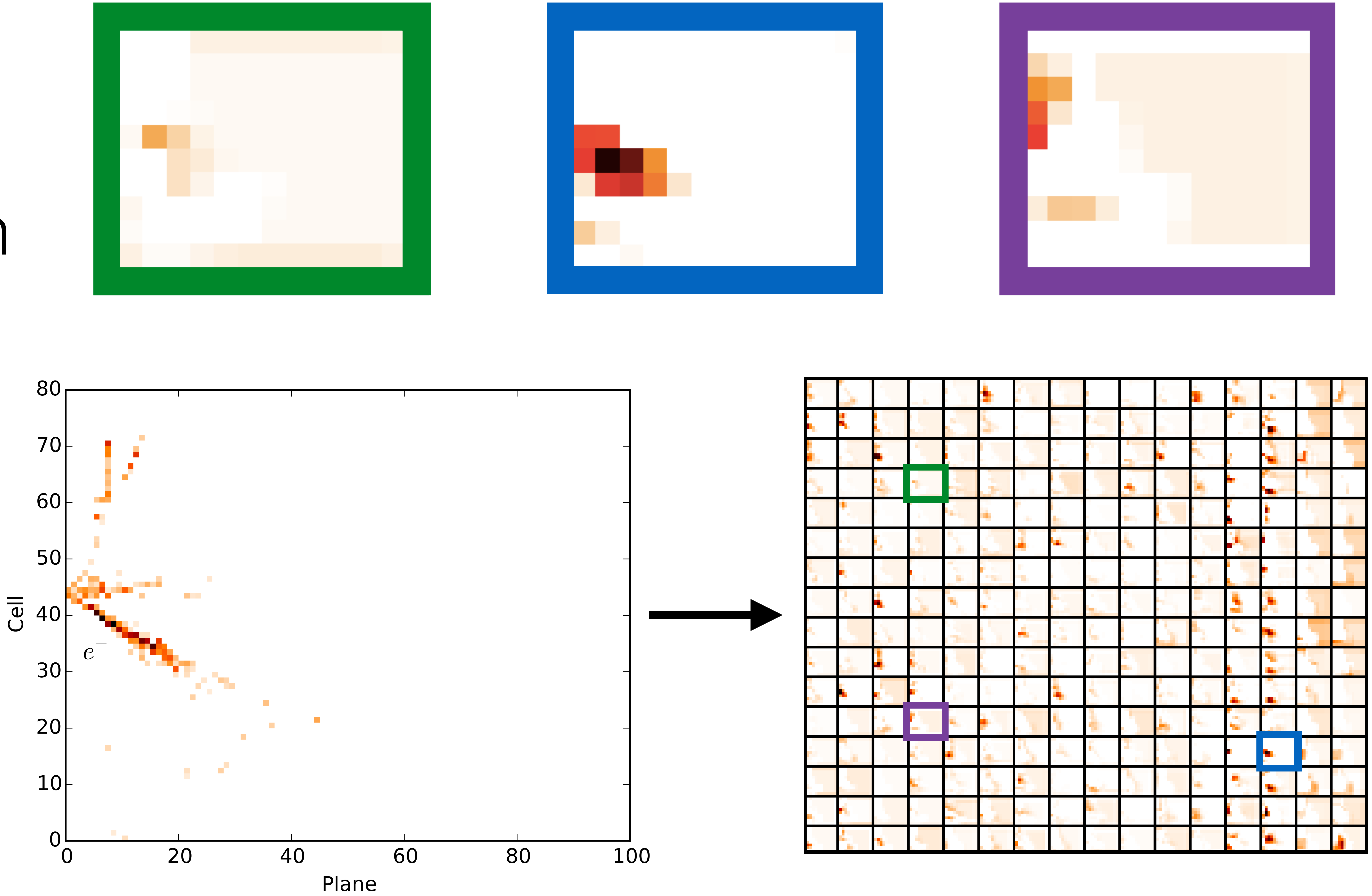

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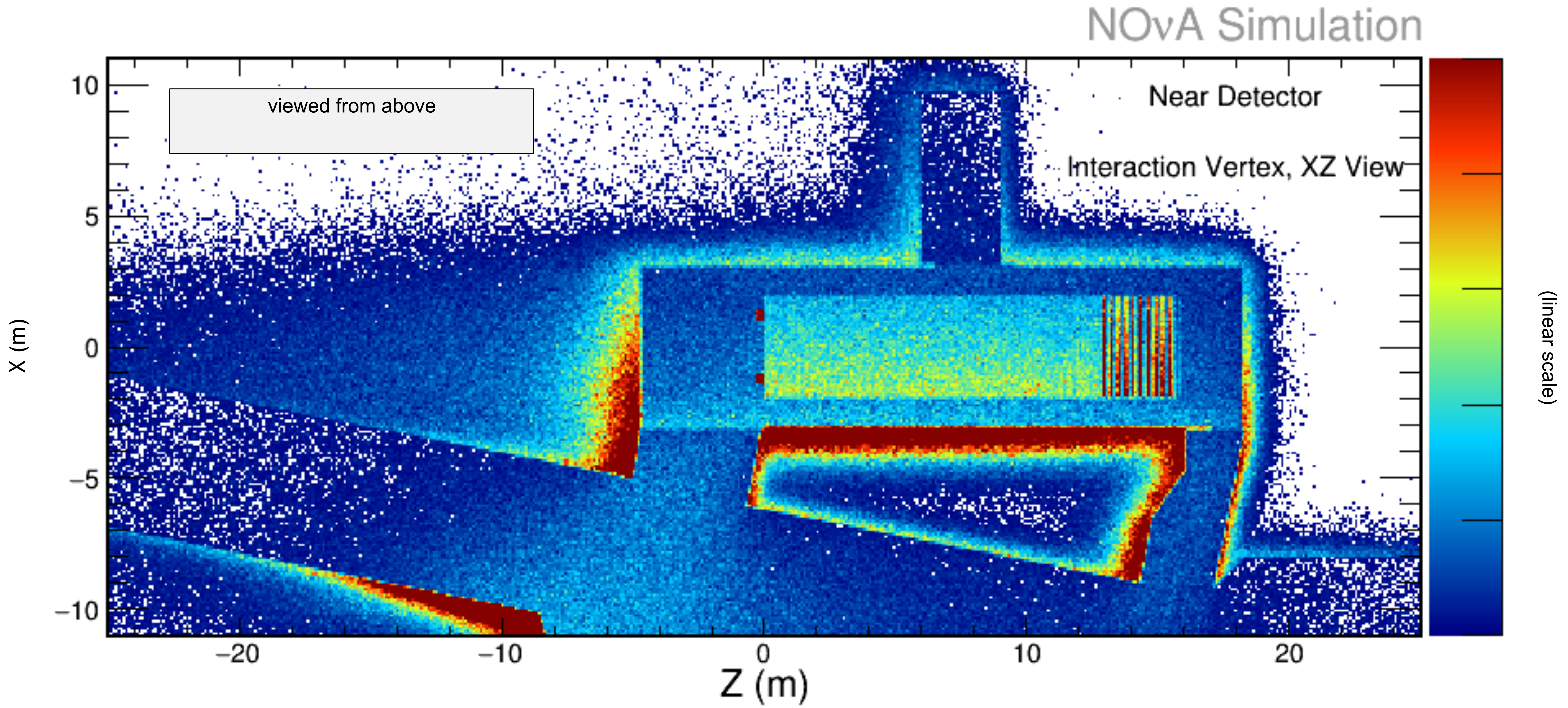
Simulation

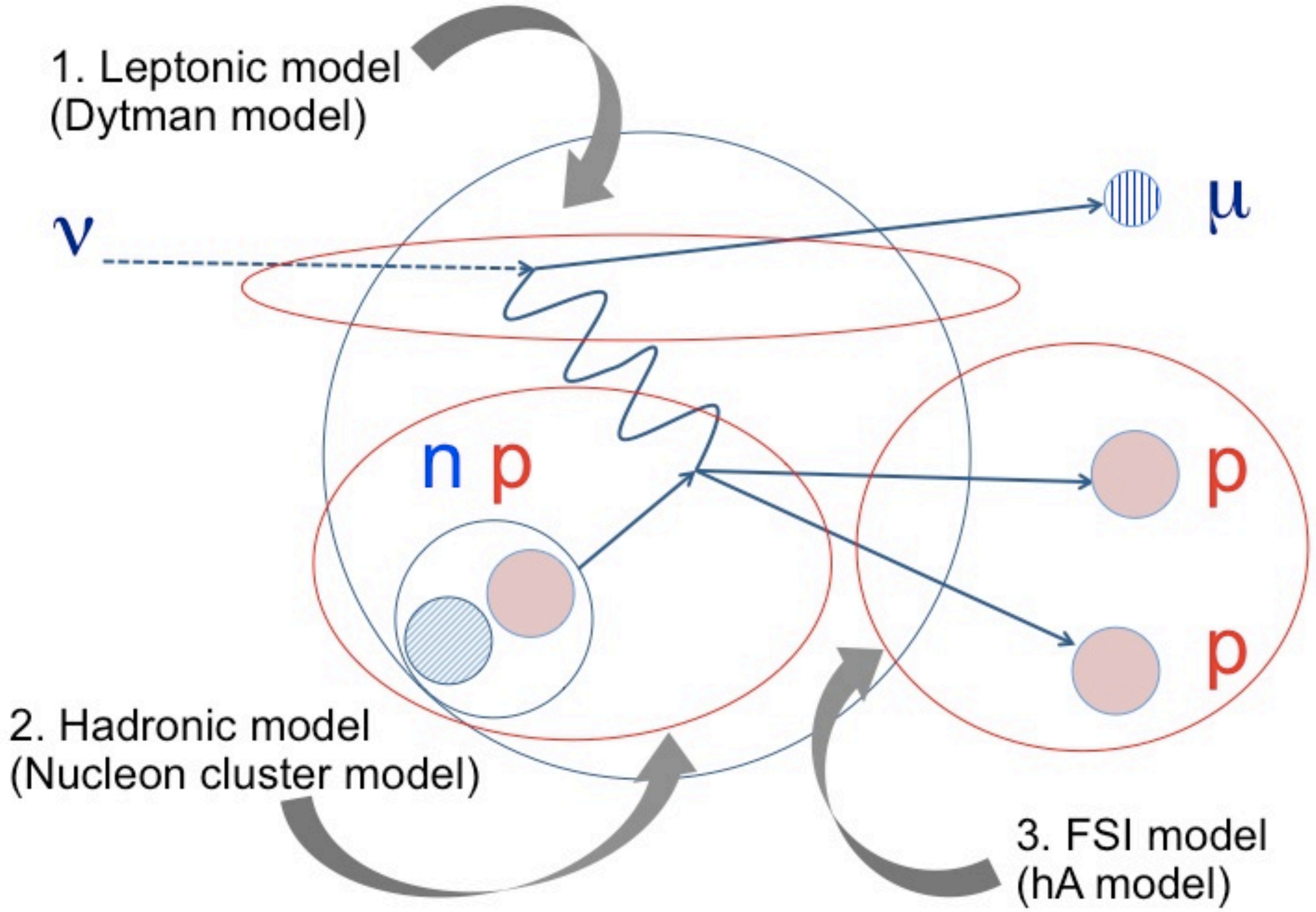
- Beam hadron production, propagation, neutrino flux: **GEANT4/External Data**
- Cosmic ray flux: **Data Triggers**
- Neutrino Interactions and FSI modeling: **GENIE v2.12.2**
- Detector Simulation: **GEANT4**
- Readout electronics and DAQ: **Custom simulation routines**

Simulation: Locations of neutrino interactions that produce activity in the Near Detector



Retuned Interaction Modeling

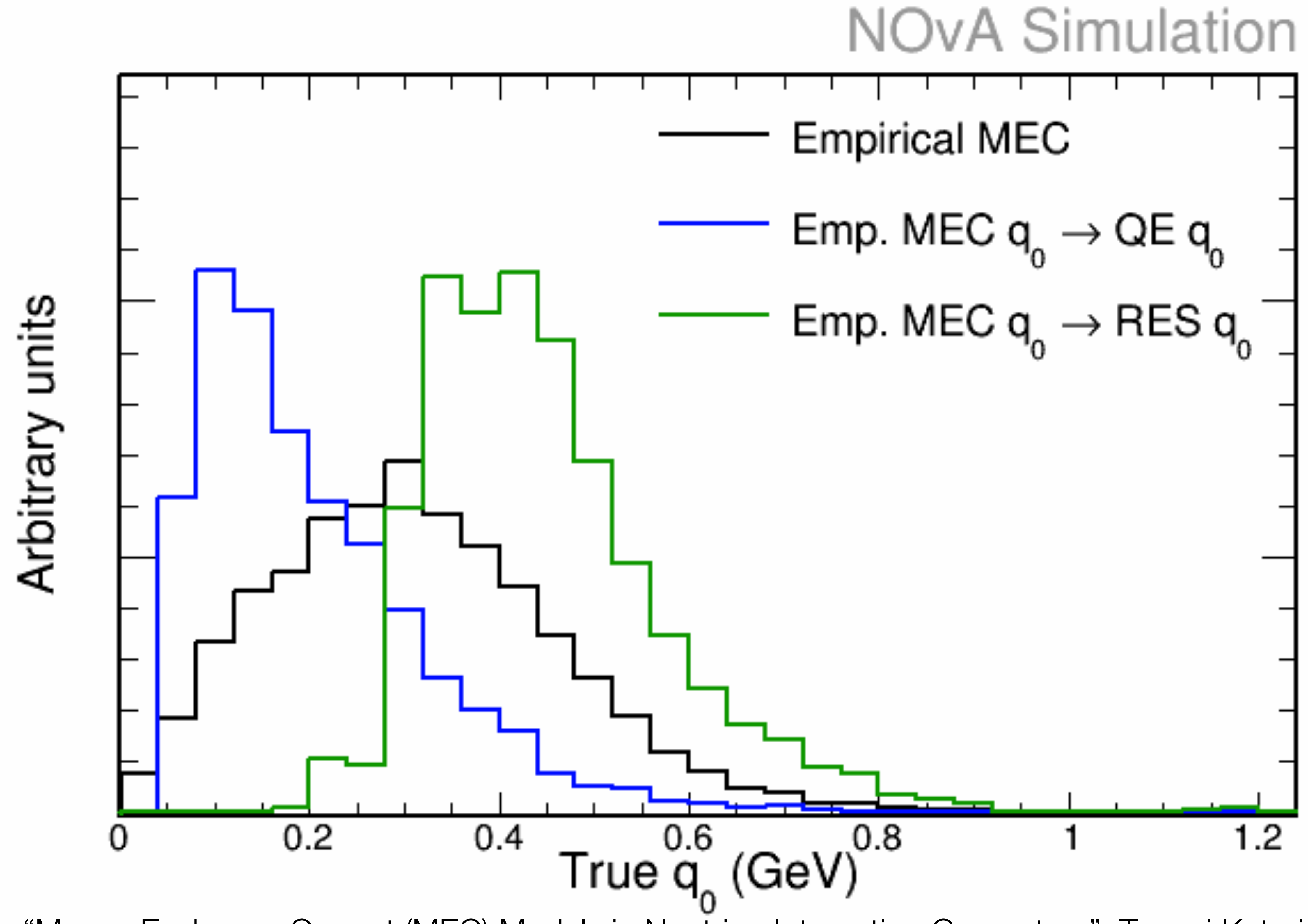
- Nuclear effects on the initial state (nuclear charge screening/"RPA" effect) and reactions themselves (multi-nucleon ejection e.g. 2p2h via Meson Exchange Currents (MEC)) remain important components of our interaction model, particularly of the hadronic energy component of our interactions.
- Theory for these effects and how they fit together remains incomplete and model evidence ambiguous.
- Important that we not just have the best possible central value tune, but also appropriately conservative uncertainties.

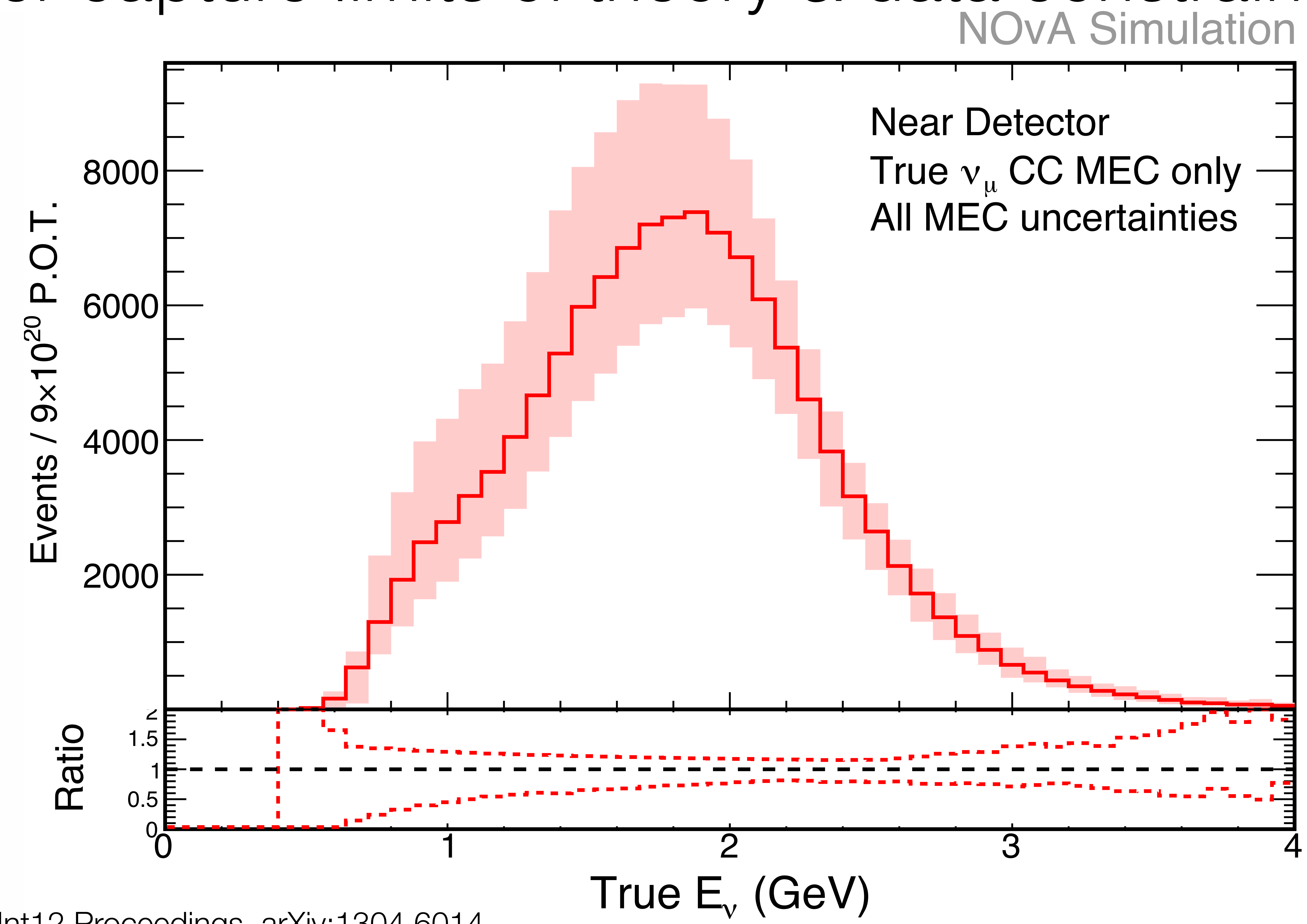


"Meson Exchange Current (MEC) Models in Neutrino Interaction Generators"
AIP Conf.Proc. 1663 (2015) 030001
Teppei Katori

Retuned Interaction Modeling

- Continue to tune MEC to match the excess in our data, now fit using default empirical MEC's* model for energy transfer to the hadronic system (q_0).
- QE RPA from the Valencia group via Richard Gran** now included in central value tune.
- New MEC and RPA uncertainties that better capture limits of theory & data constraints.





* "Meson Exchange Current (MEC) Models in Neutrino Interaction Generators", Teppei Katori, NuInt12 Proceedings, arXiv:1304.6014

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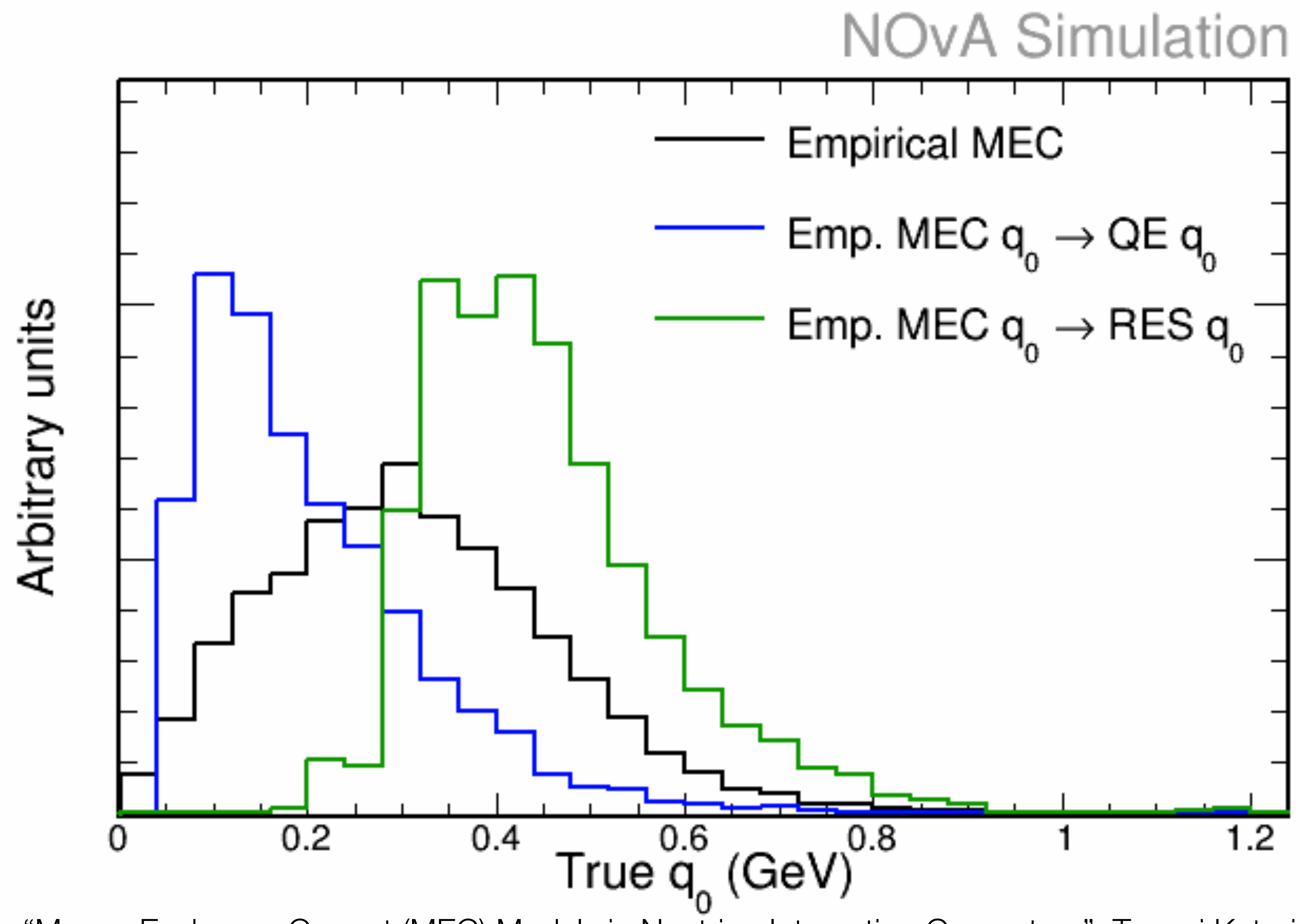

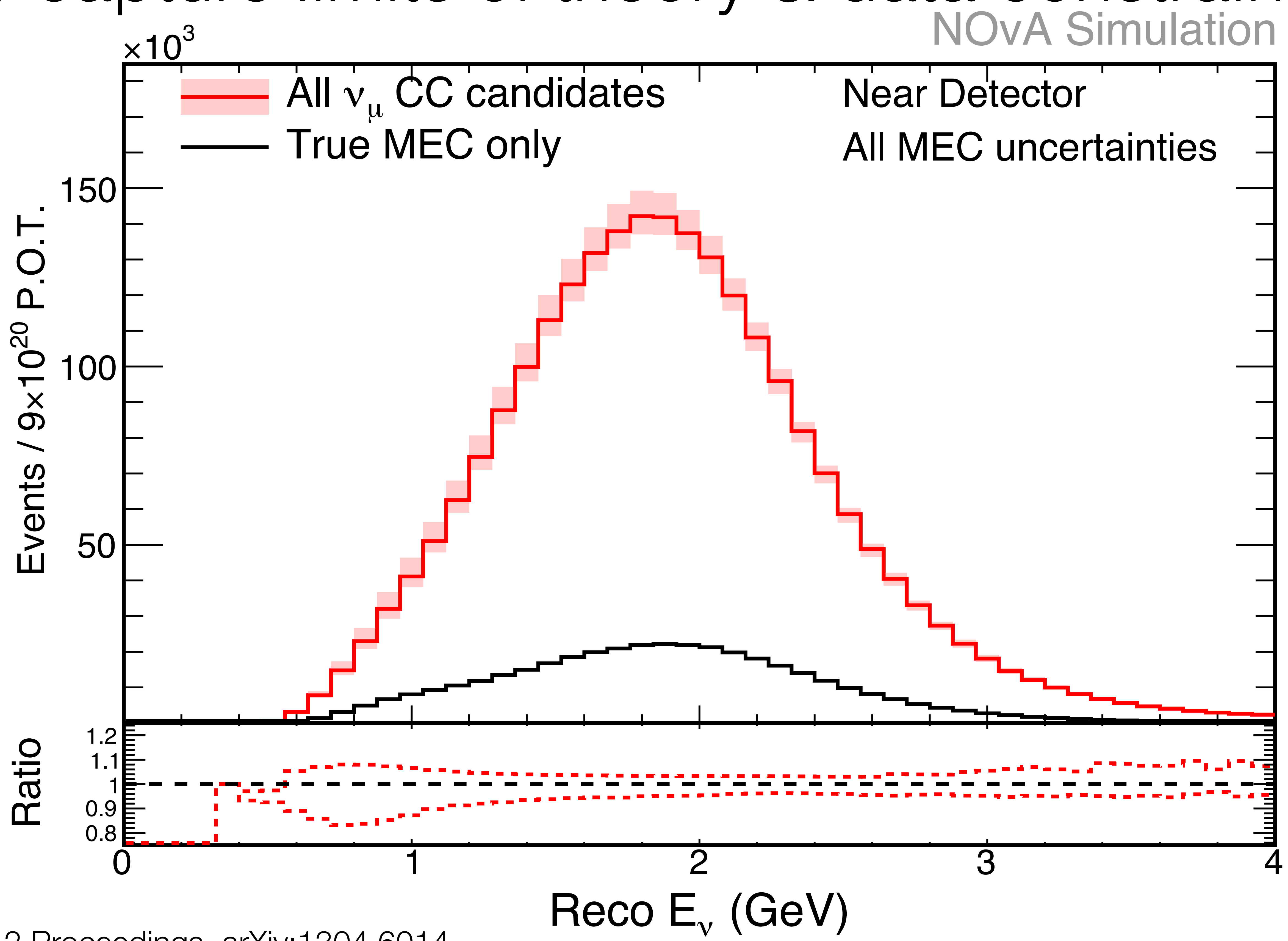

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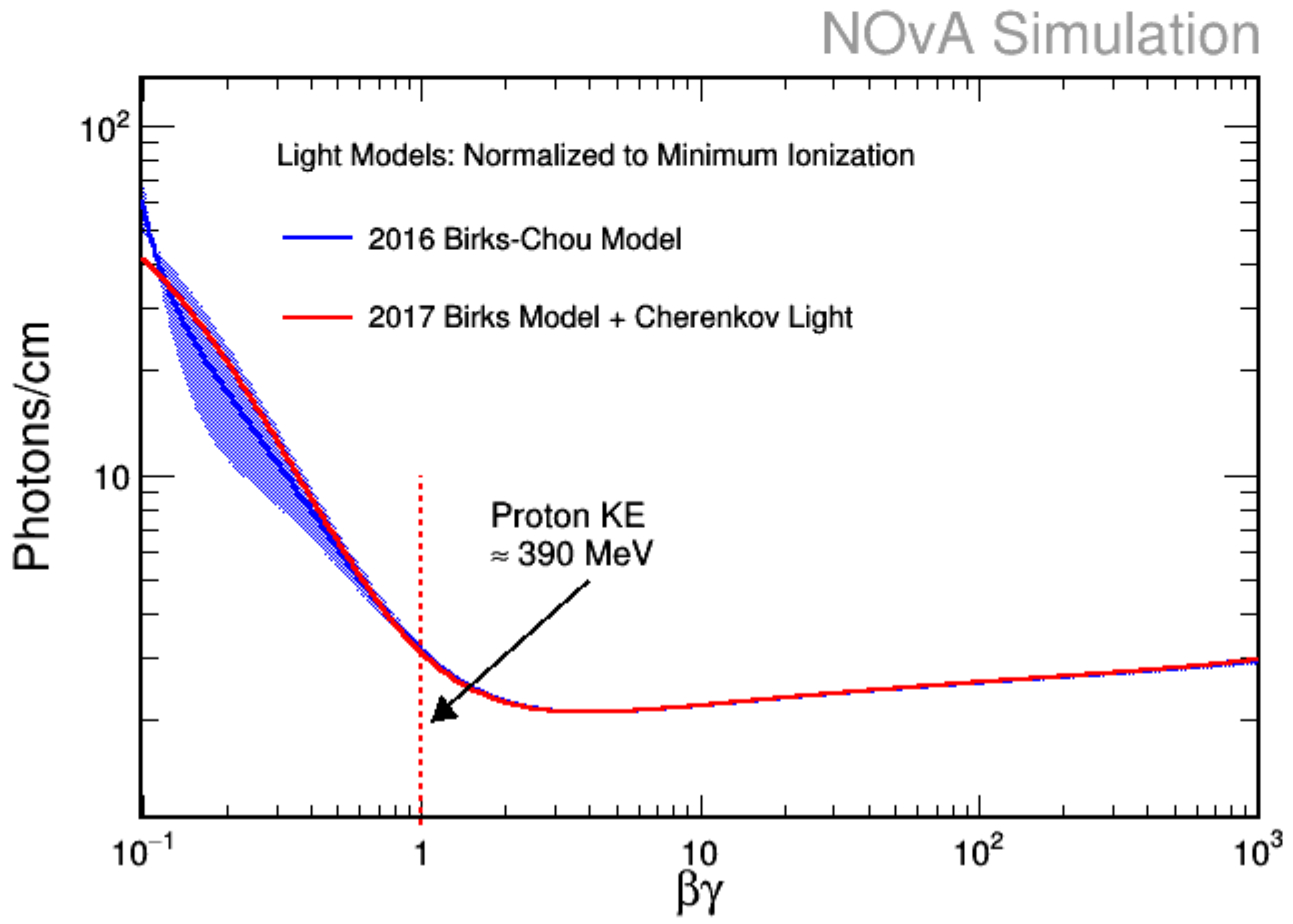
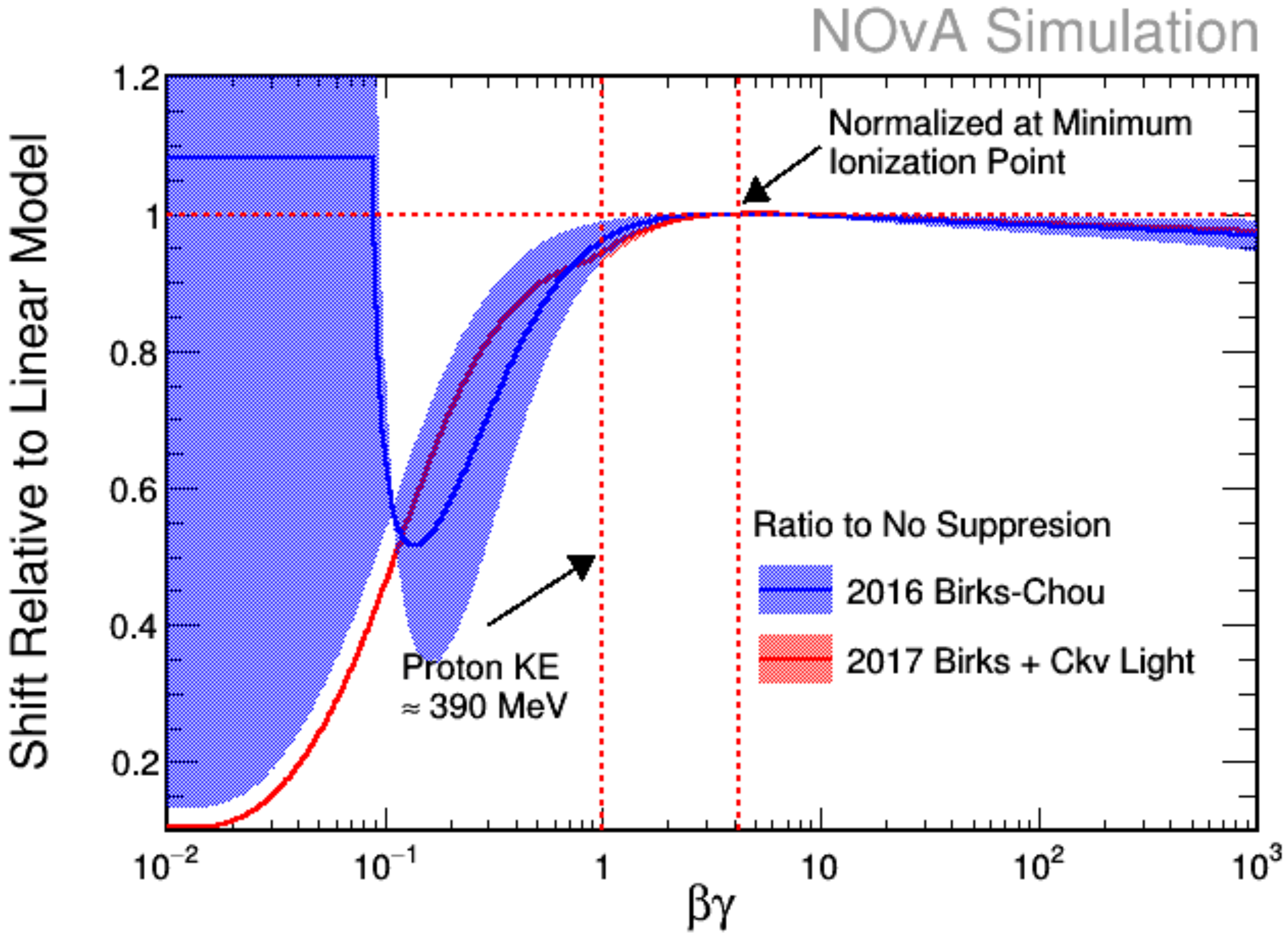
Improved Detector Simulation

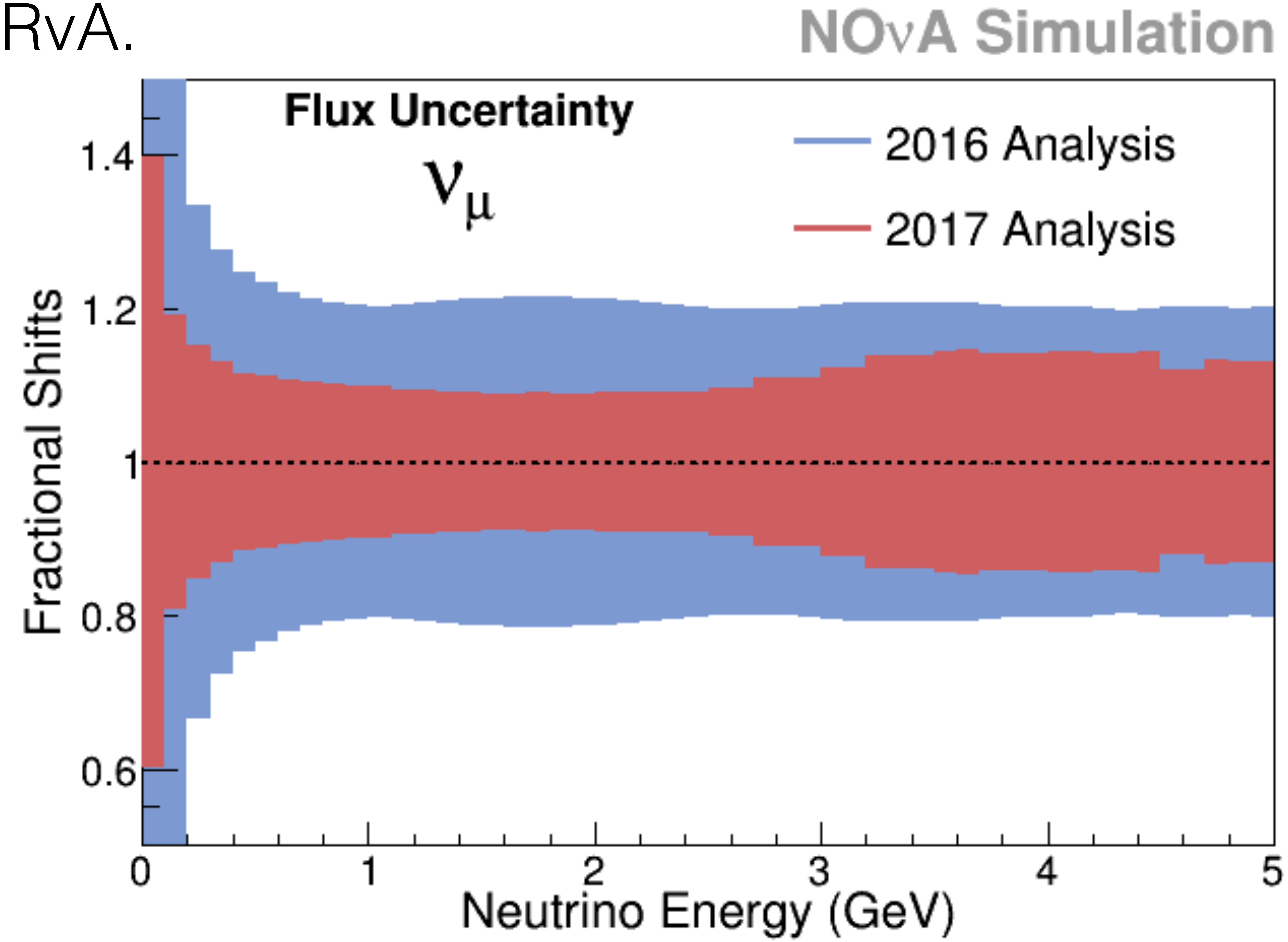
- Previously detector response uncertainties were some of our largest. Reduced by an order of magnitude in new detector simulation, driven by addition of cherenkov light.
- Absorbed and re-emitted Cherenkov light is a small but important in modeling the detector response to hadronic activity.
- Expected energy resolution for ν_μ CC events moves from 7% to 9%.





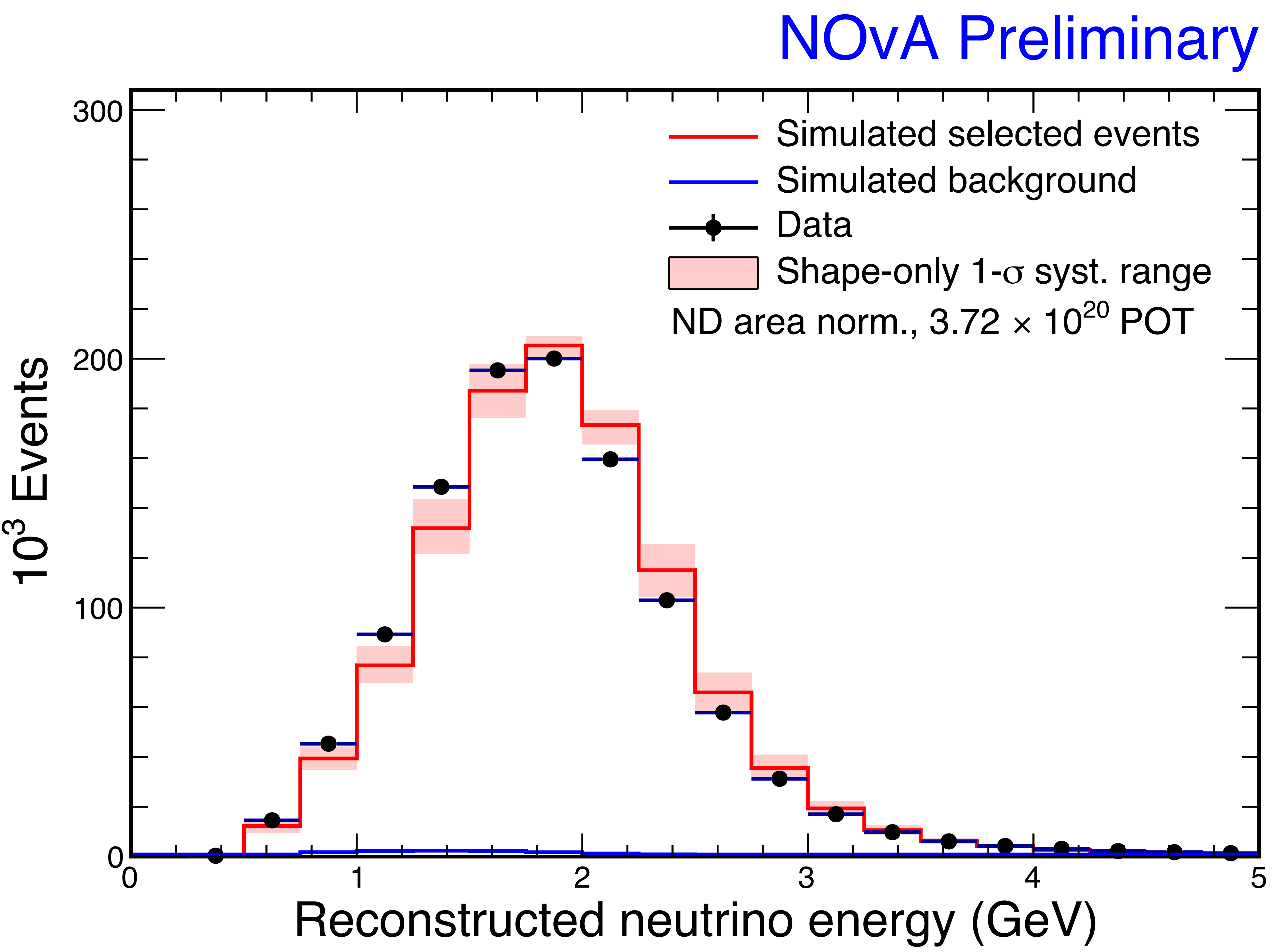
New Flux

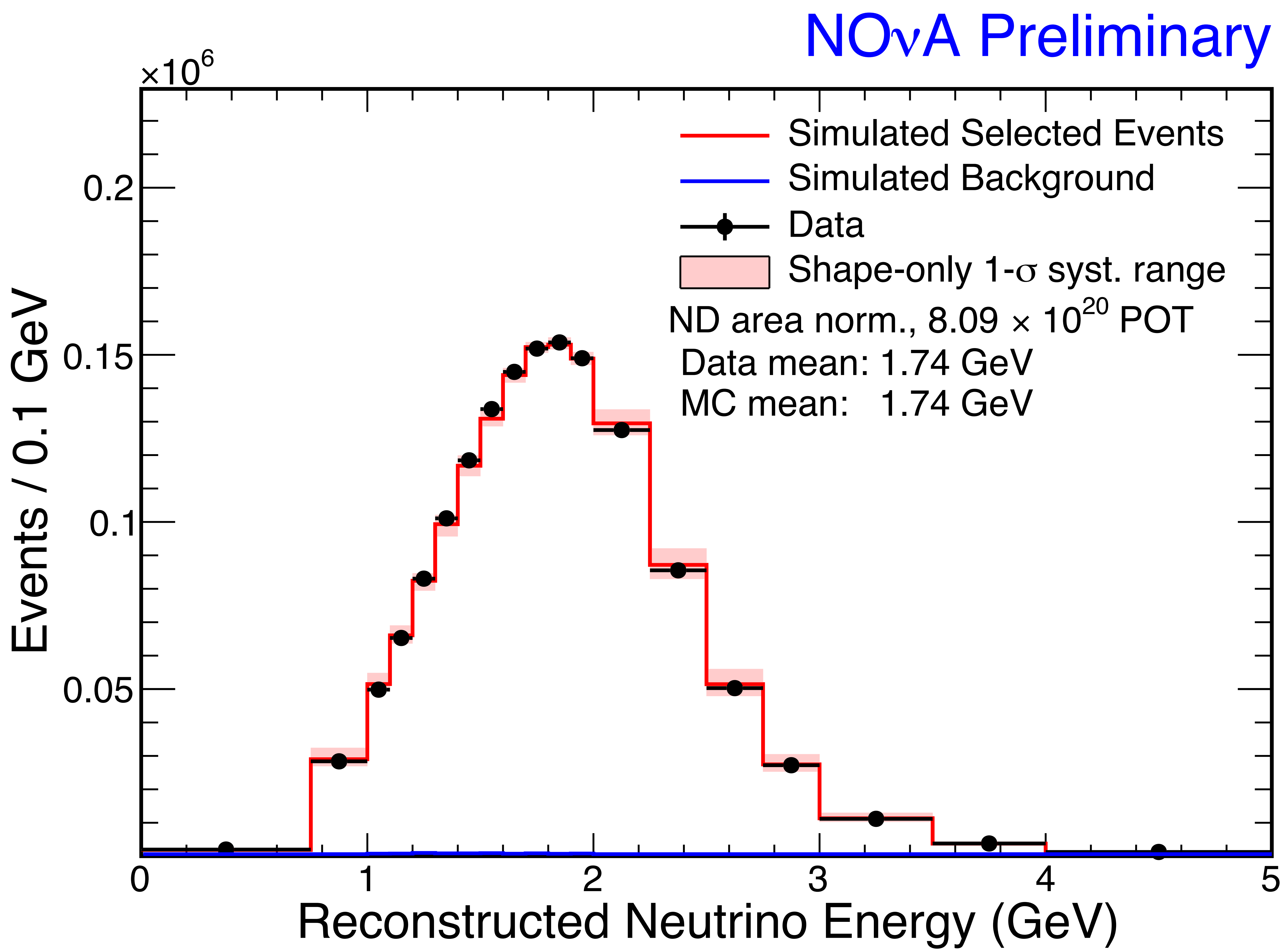
- A new data driven flux, Package to Predict the FluX (**PPFX**), based on thin target hadron production data from NA49 and MIPP.
- Comes with greatly reduced flux uncertainties.
- Pioneered at MINERvA.



"Neutrino Flux Predictions for the NuMI Beam"
MINERvA Collaboration (L. Aliaga et al.)
Phys.Rev. D94 (2016) no.9, 092005

Simulation





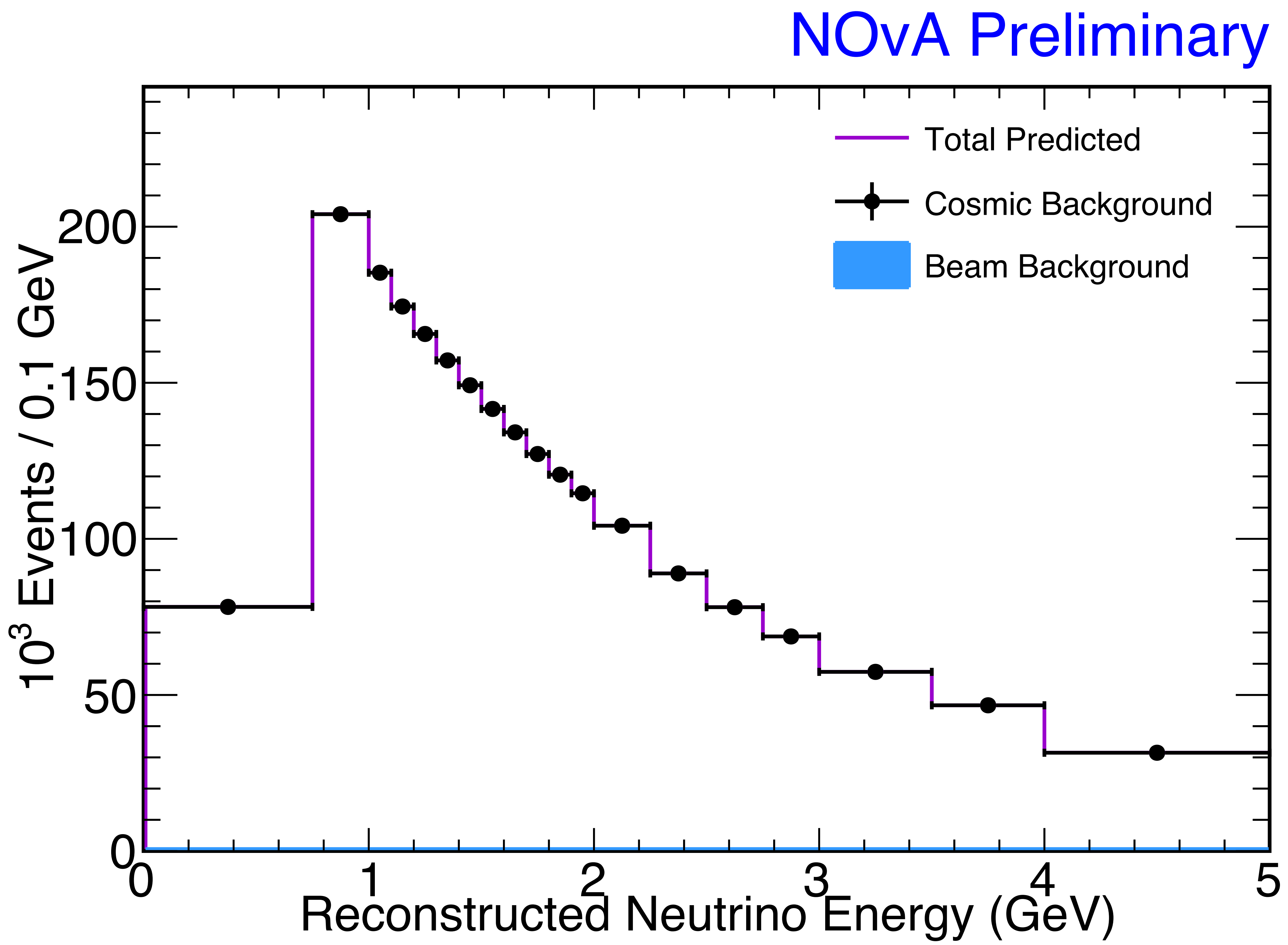
Old → New

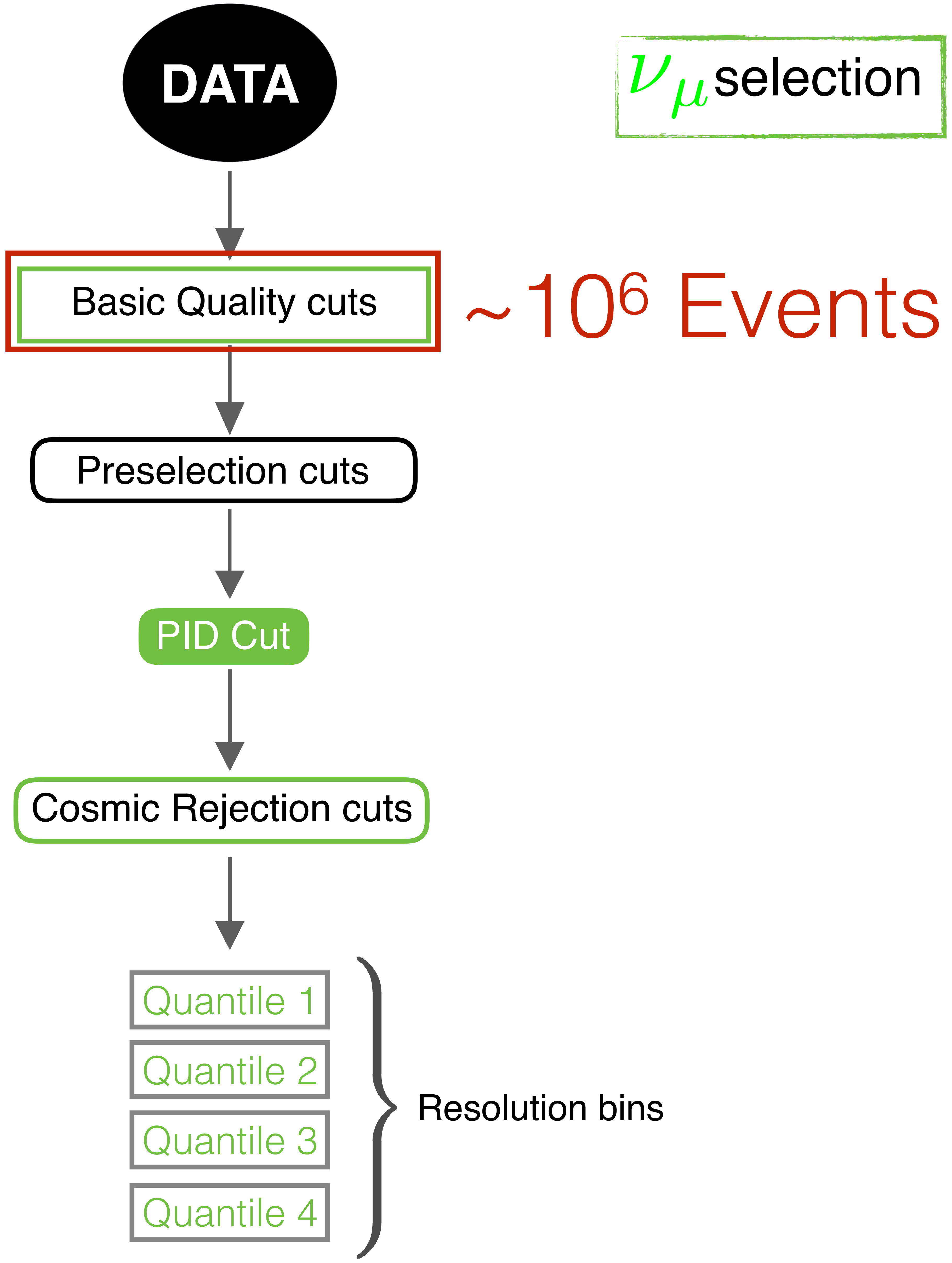
ν_μ Disappearance

1. Select, measure & characterize ND and FD ν_μ events.
2. Extrapolate beam expectation to FD and measure cosmic expectation from FD data out of the beam spill window.
3. Compare measured FD energy spectra to expectation.

Improved ν_μ Selection

Even with excellent timing resolution cosmogenic activity at the Far Detector remains a challenging background due to raw rate.





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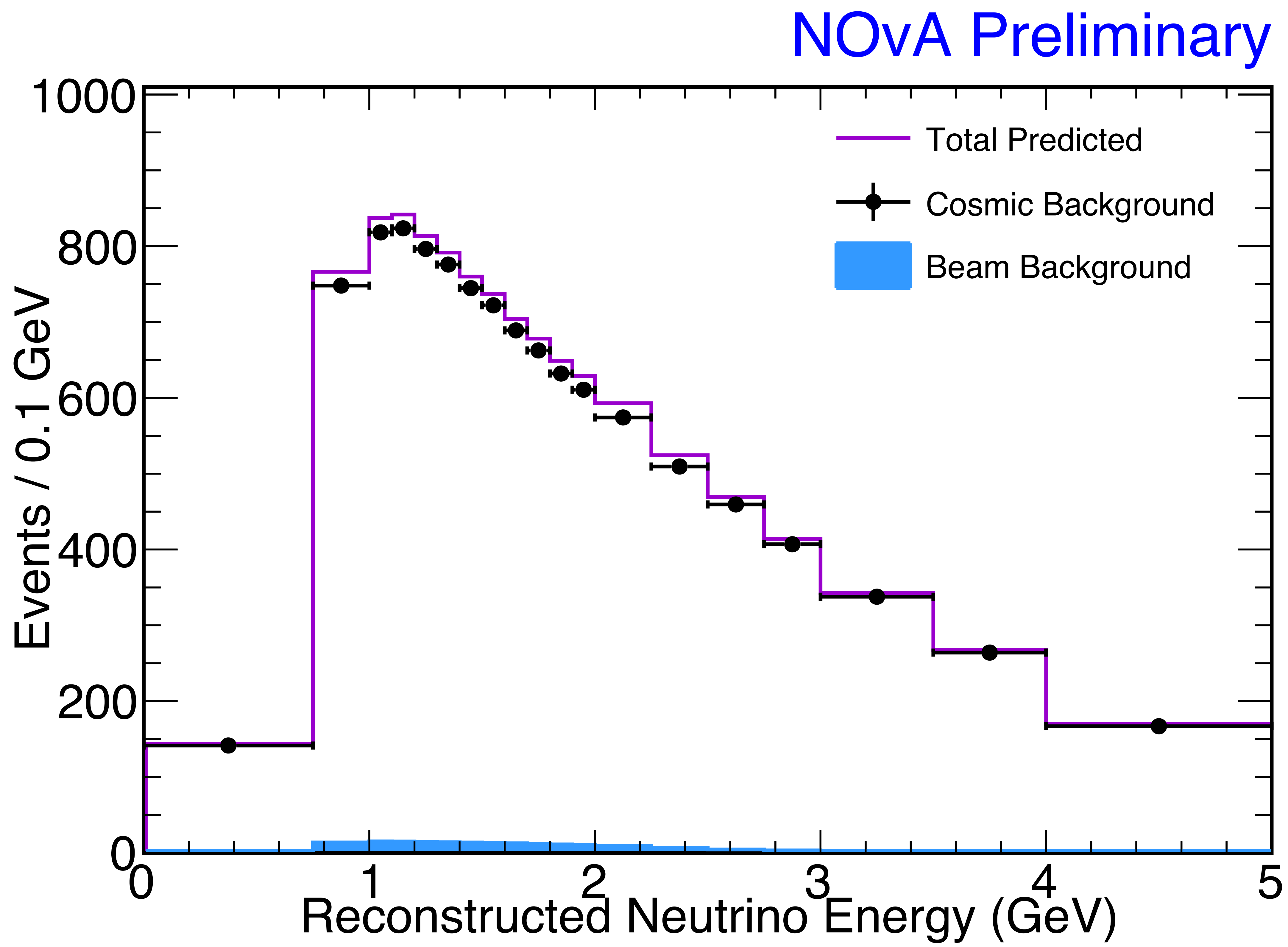
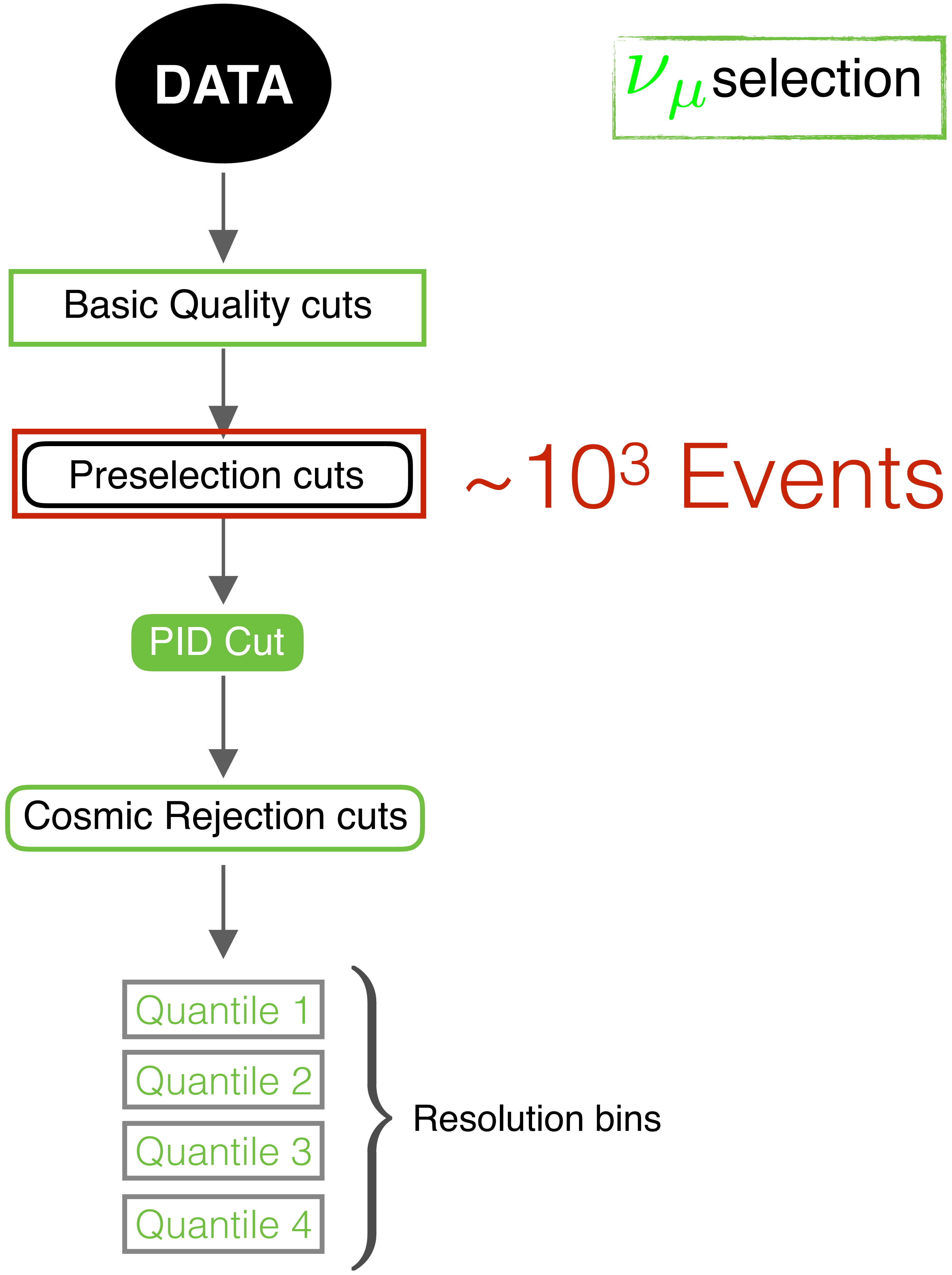
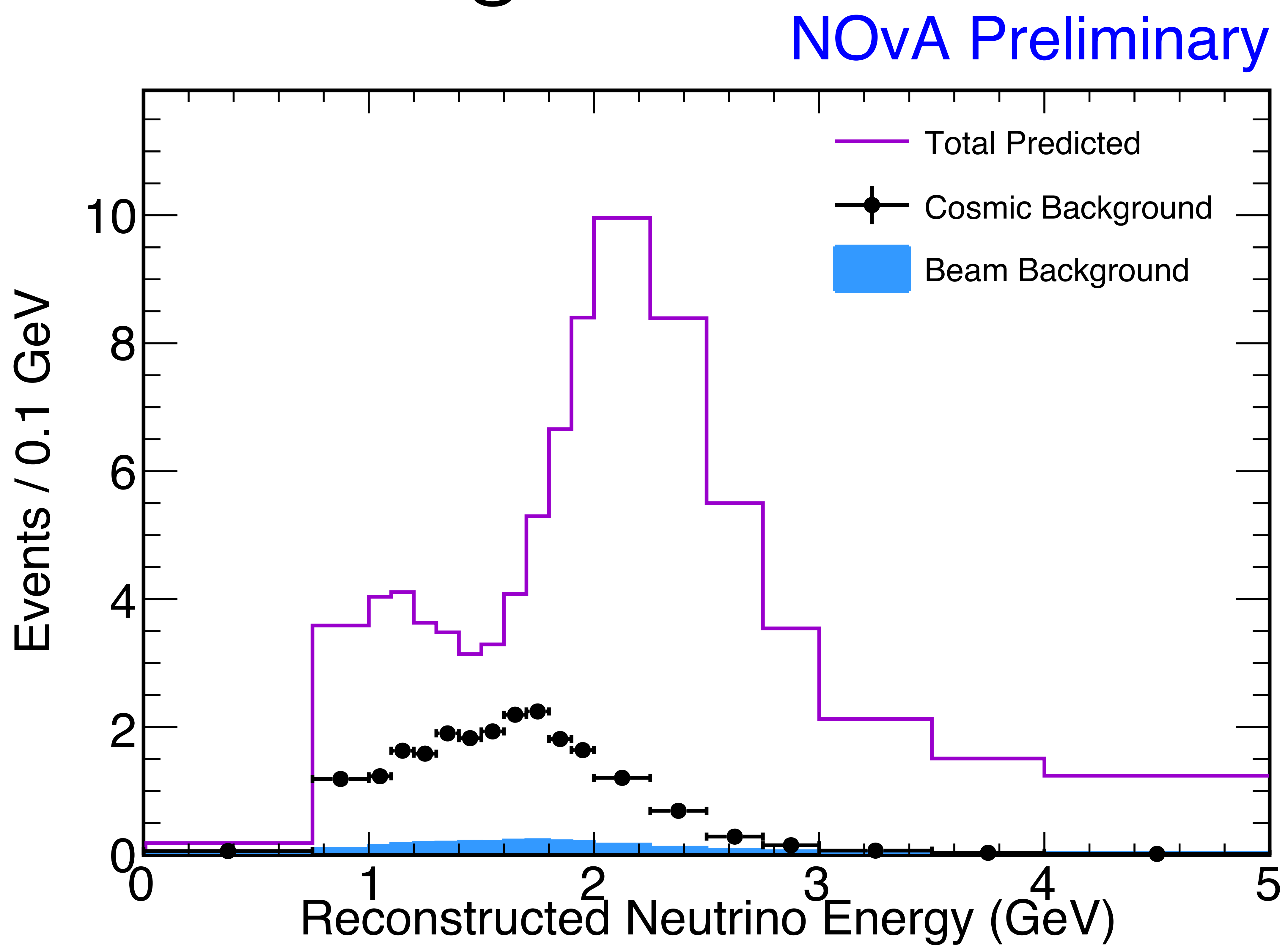
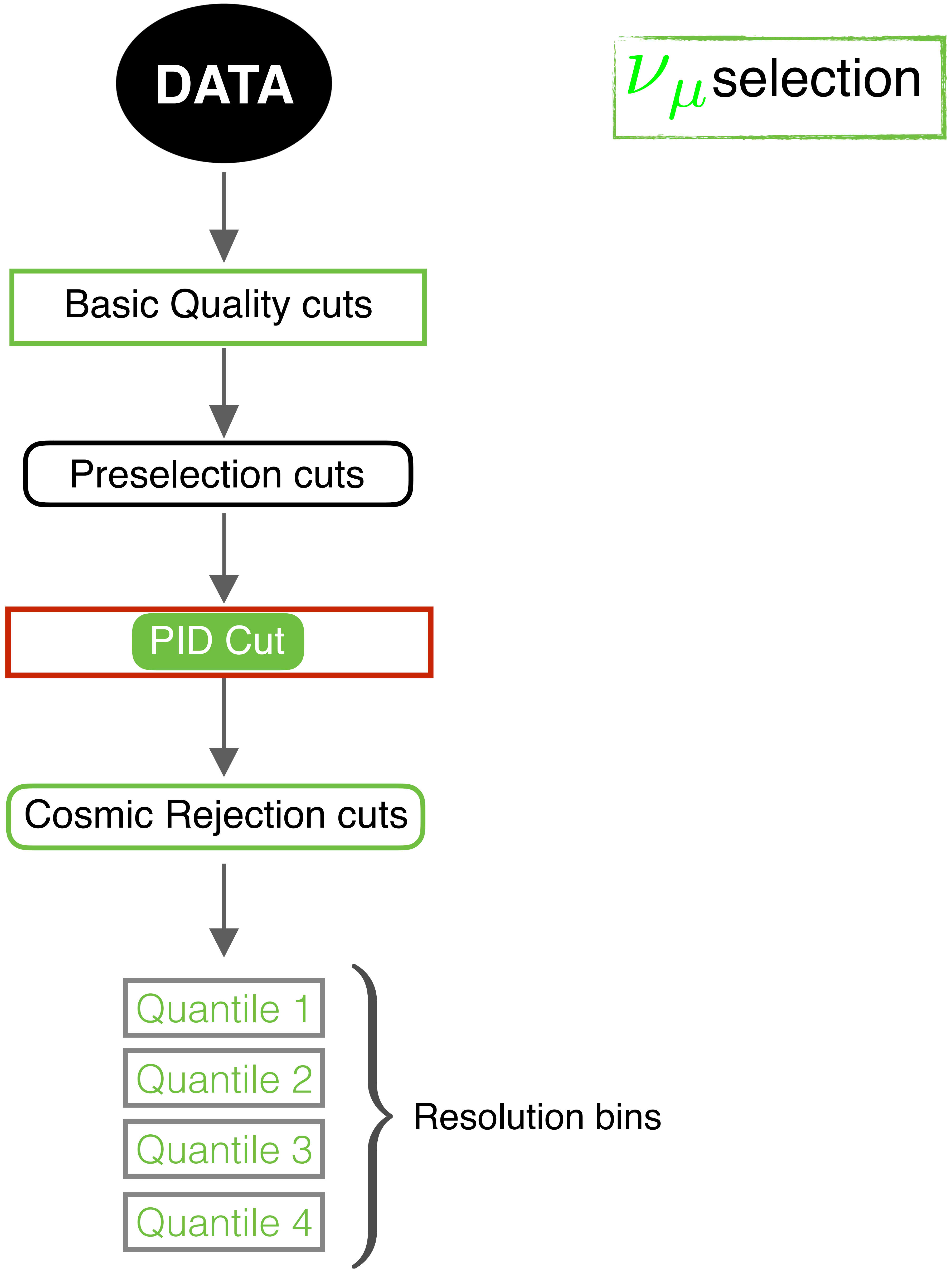




Improved ν_μ Selection

- New selection using CVN, a retuned cosmic rejection BDT, and a new PID cut
- Equivalent background rejection with 11% more signal selected.





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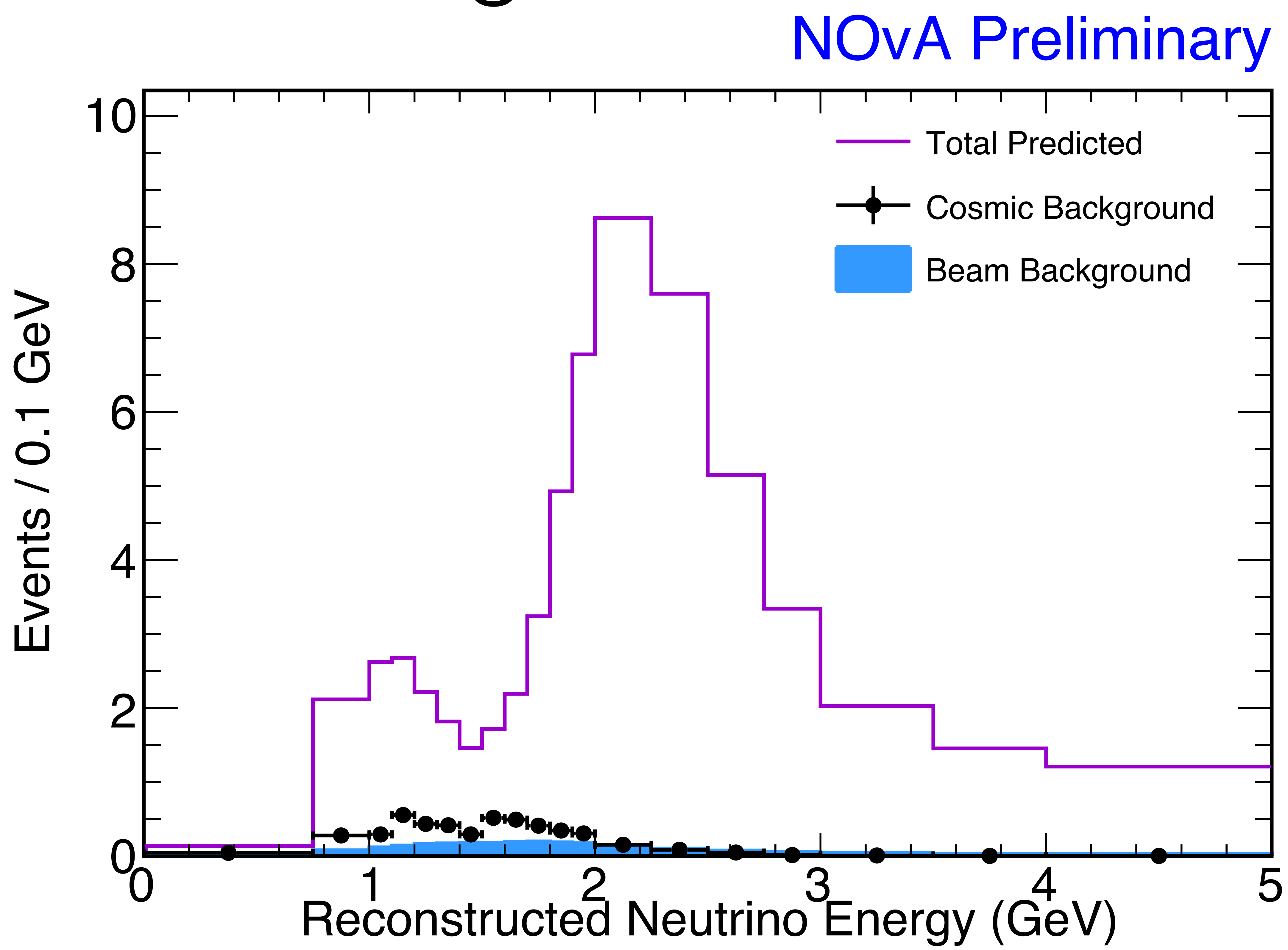
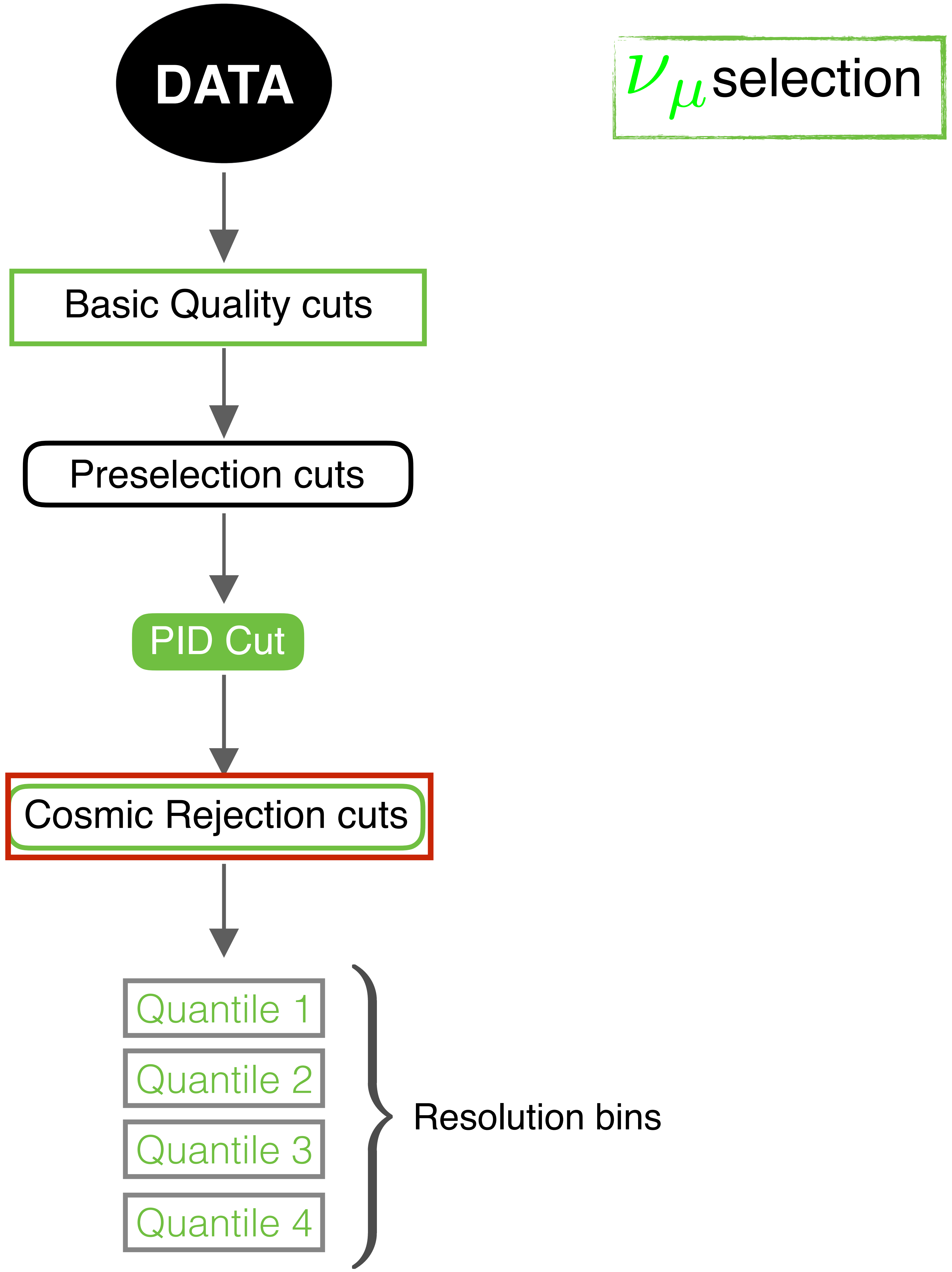
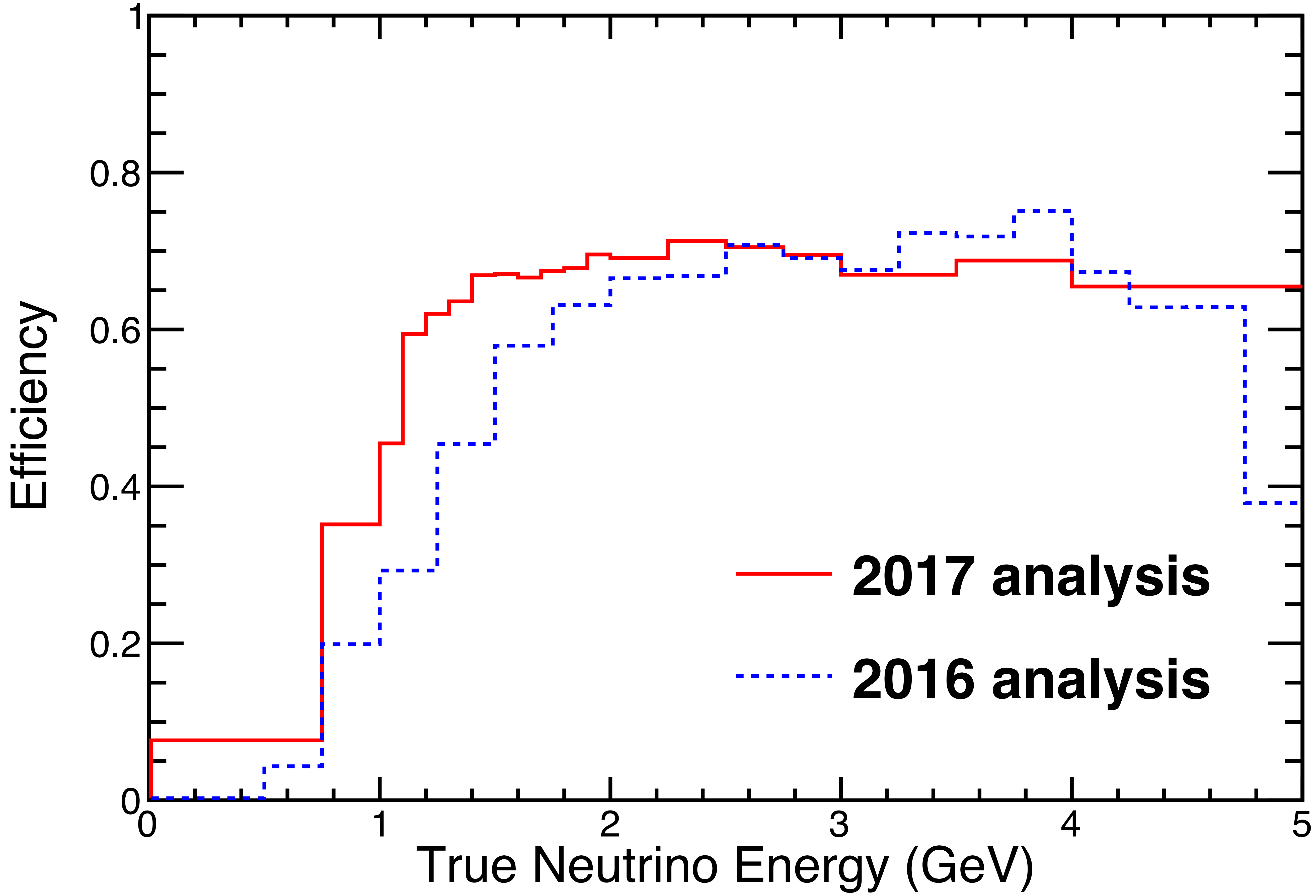




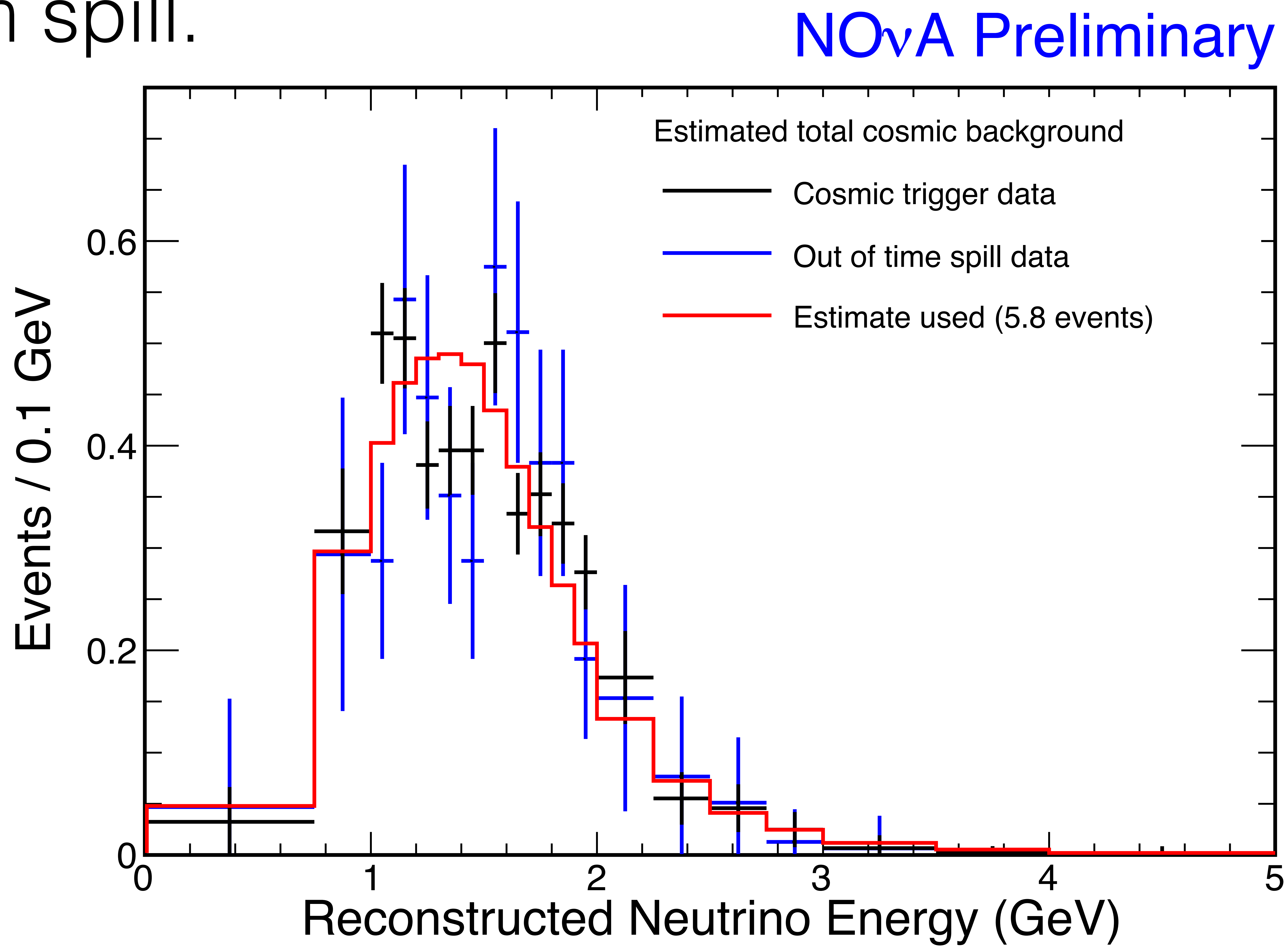
Improved ν_μ Selection

- Improvement is most pronounced in key low energy region.
- Expected overlap between old and new PIDs is consequentially low, particularly in cosmic background events.



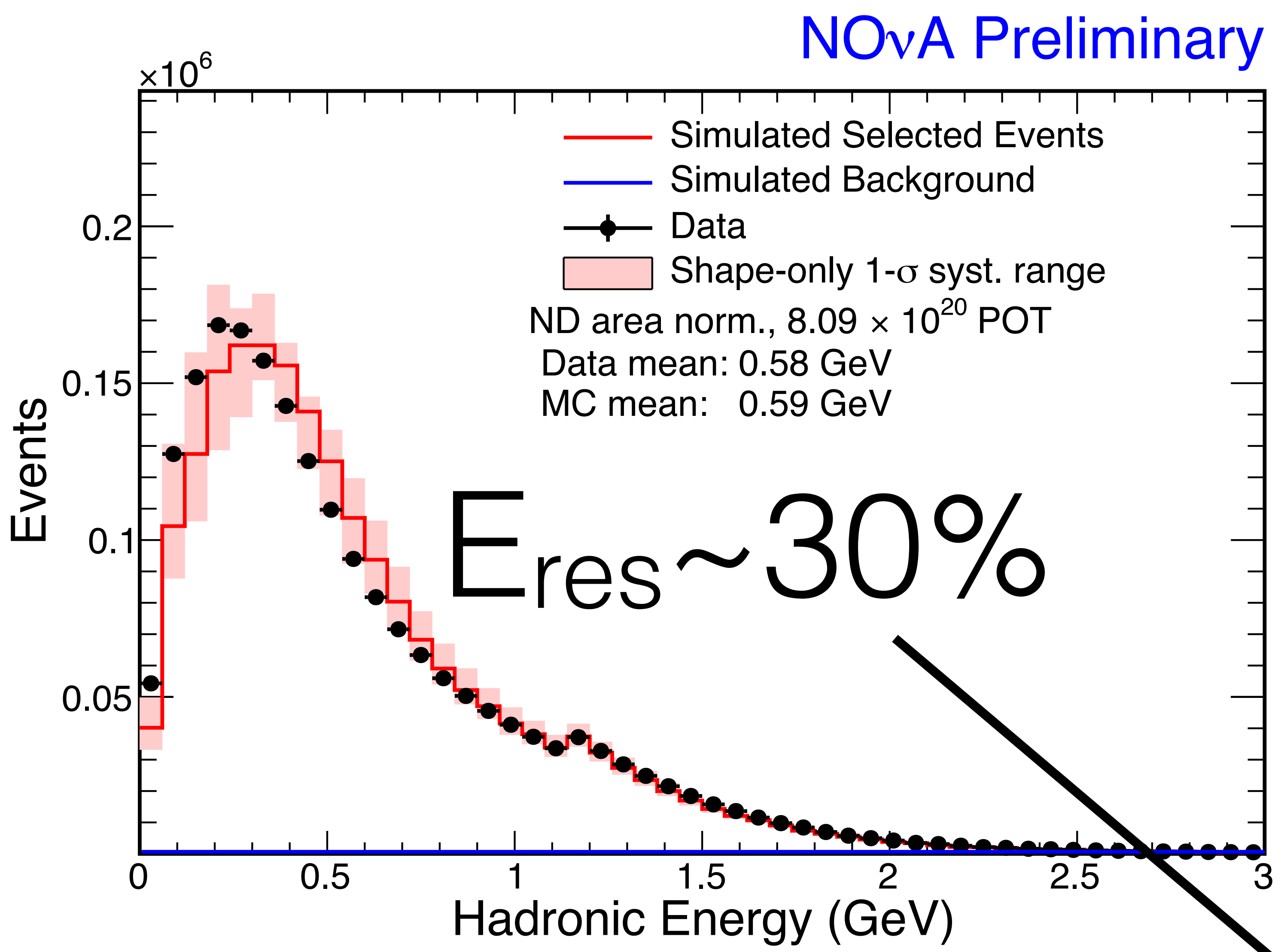
Cosmic Background Prediction

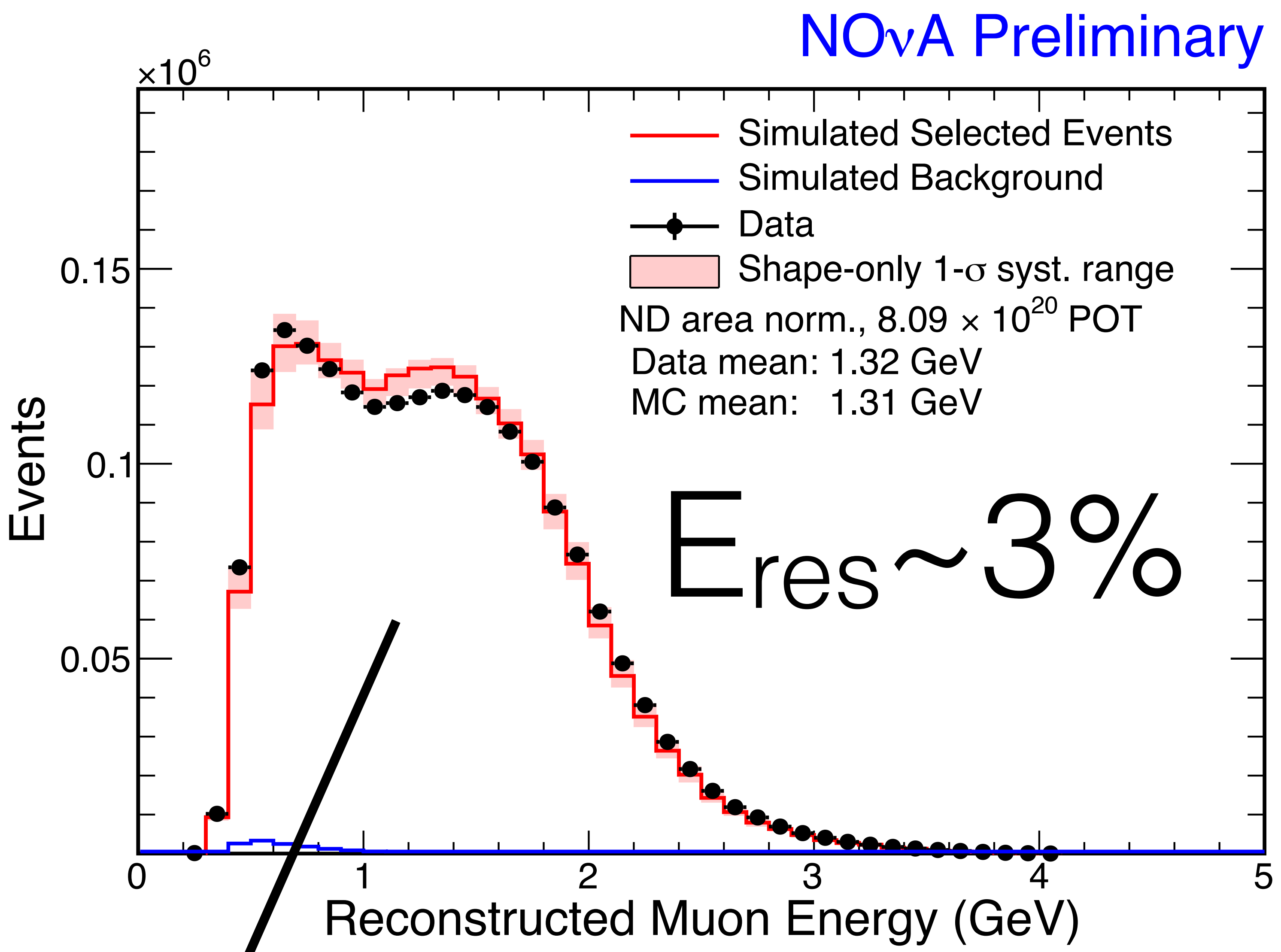
- Cosmic backgrounds are characterized using cosmic activity recorded out of the beam spill.
- Final cosmic rate comes from cosmic activity recorded adjacent to the beam spill, ensuring perfectly matched detector performance.

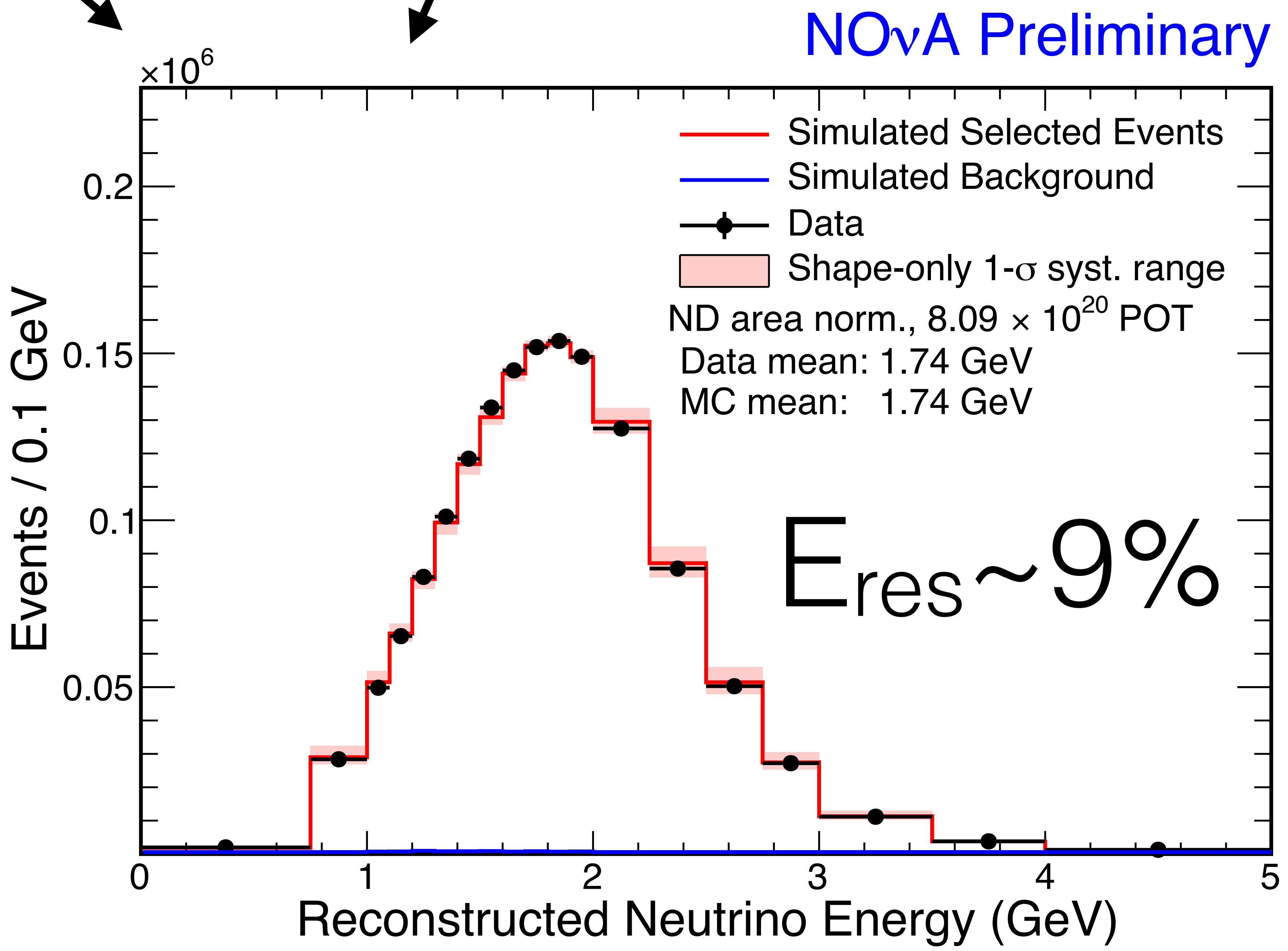


ν_μ Energy Estimation

- Final reconstructed energy combines E_{had} and E_μ via a piecewise linear fit.
- Observed ND spectrum is converted to true energy using MC expectation, extrapolated to FD using a Far/Near flux ratio, and then converted to an expected reconstructed energy spectra.

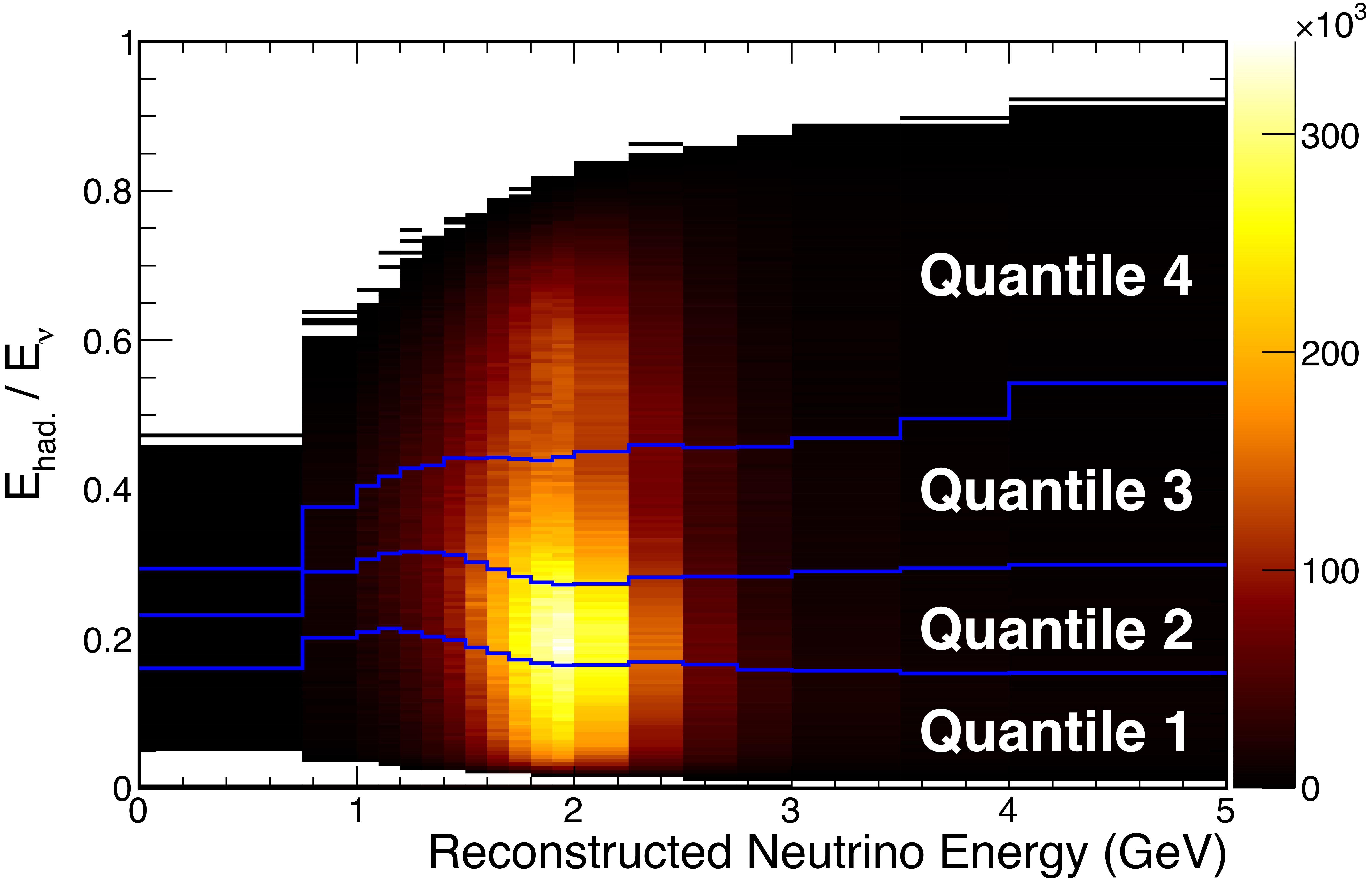






Resolution Bins

- Four bins of equal populations in FD, split in hadronic energy fraction as a function of reconstructed neutrino energy.
- Resolution varies from ~6% to ~12% from the best to worst resolution bins.



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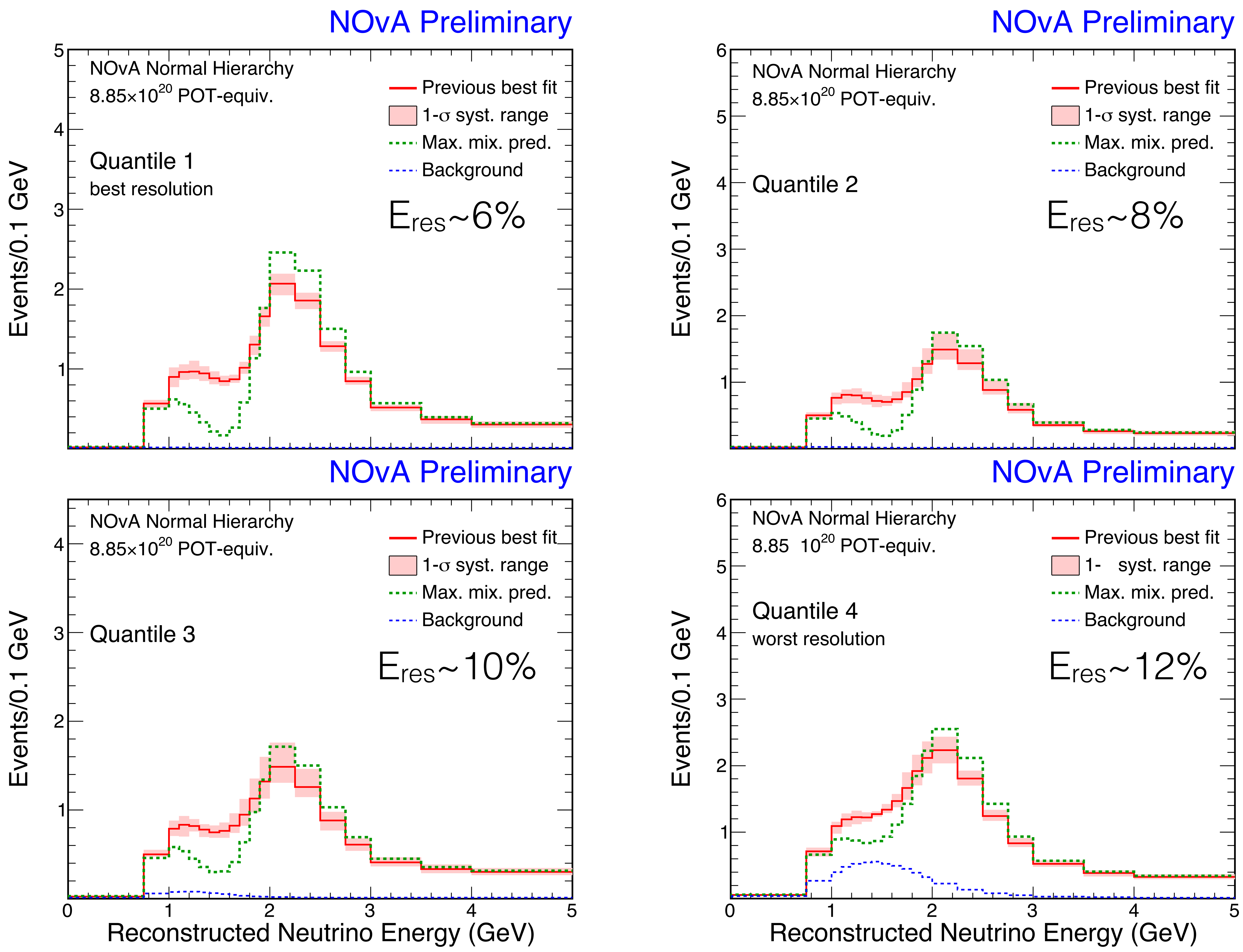
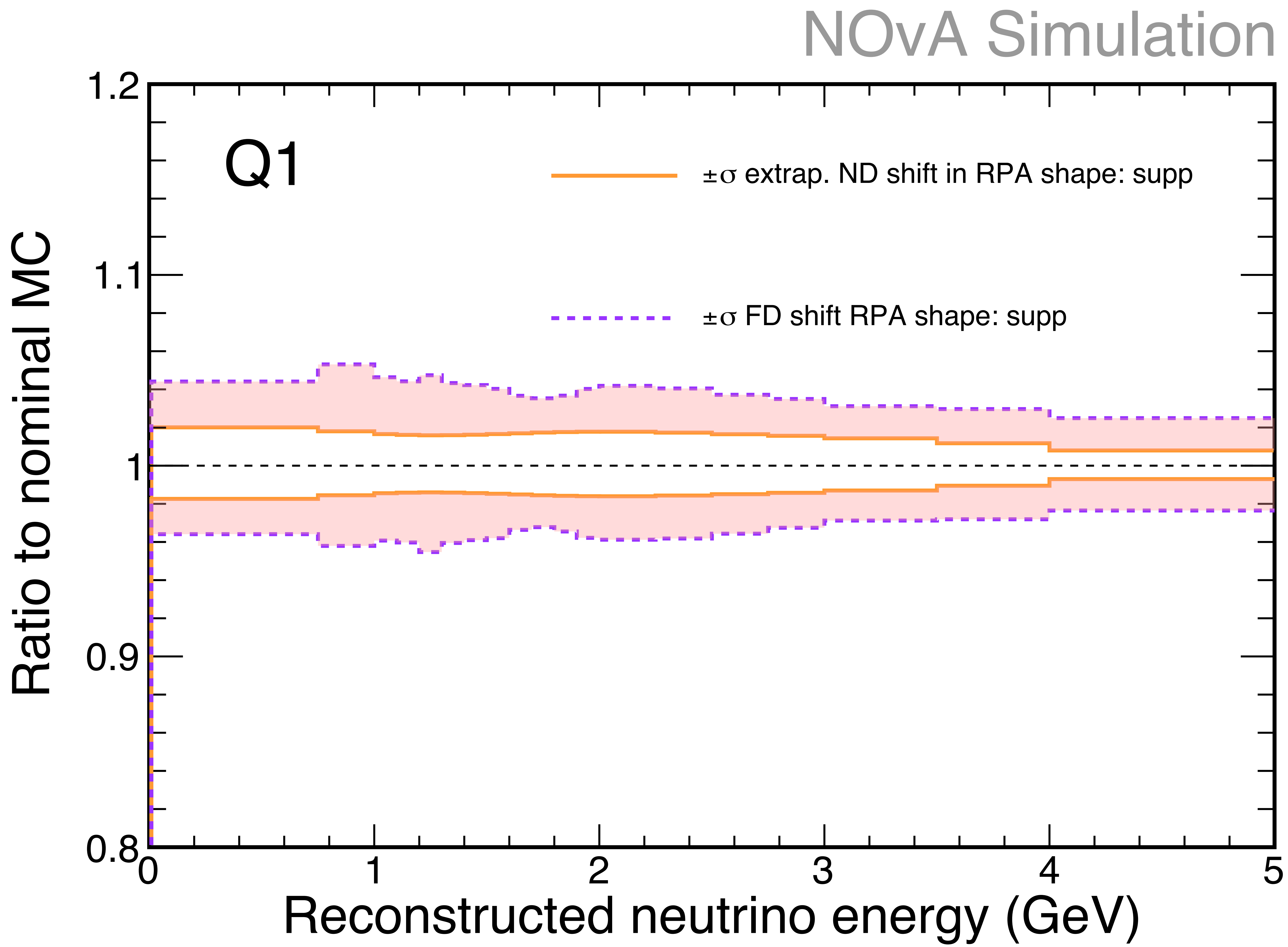


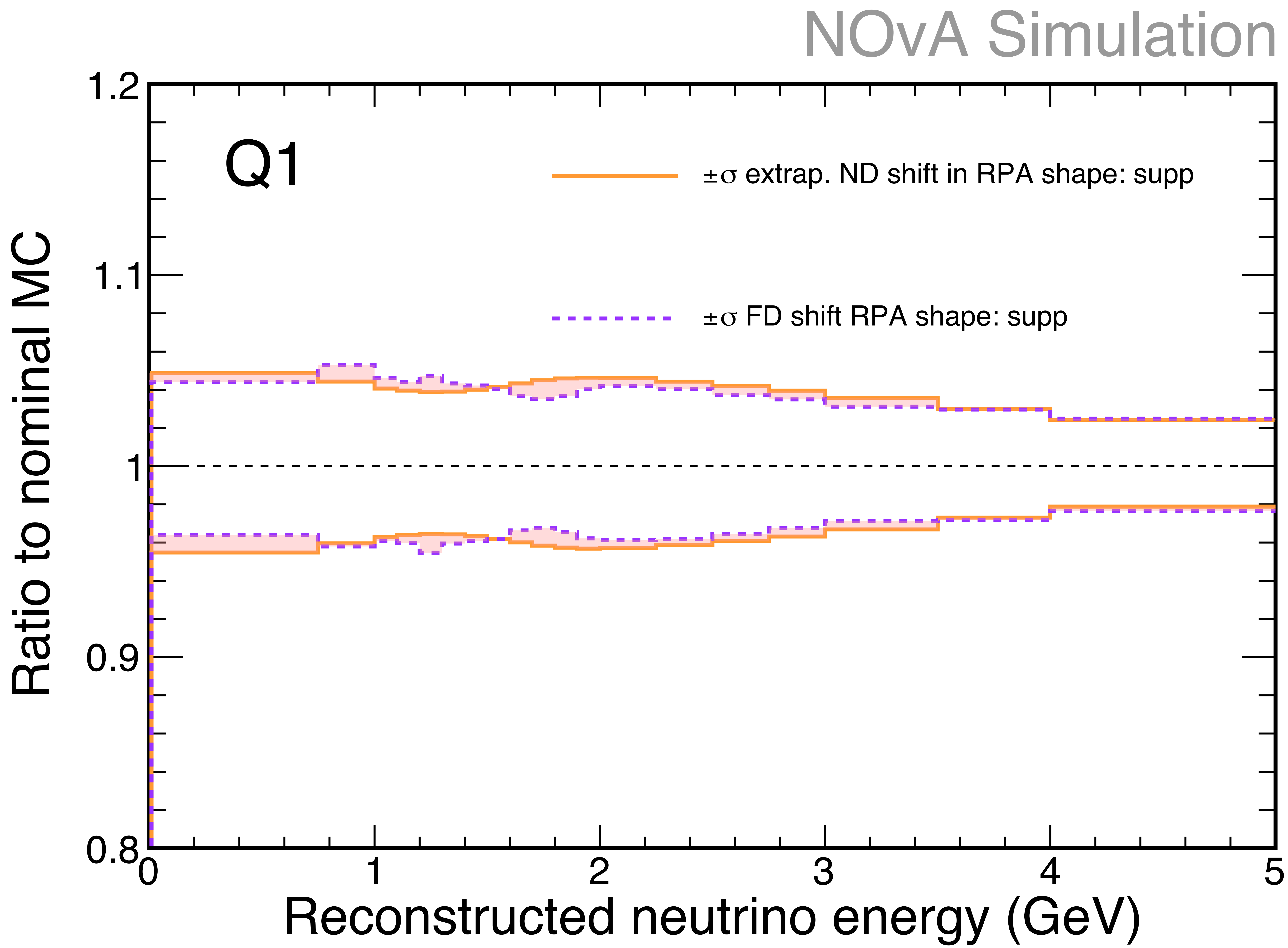
Resolution Binned Extrapolation

RPA shape uncertainty **extrapolation in one spectra.**

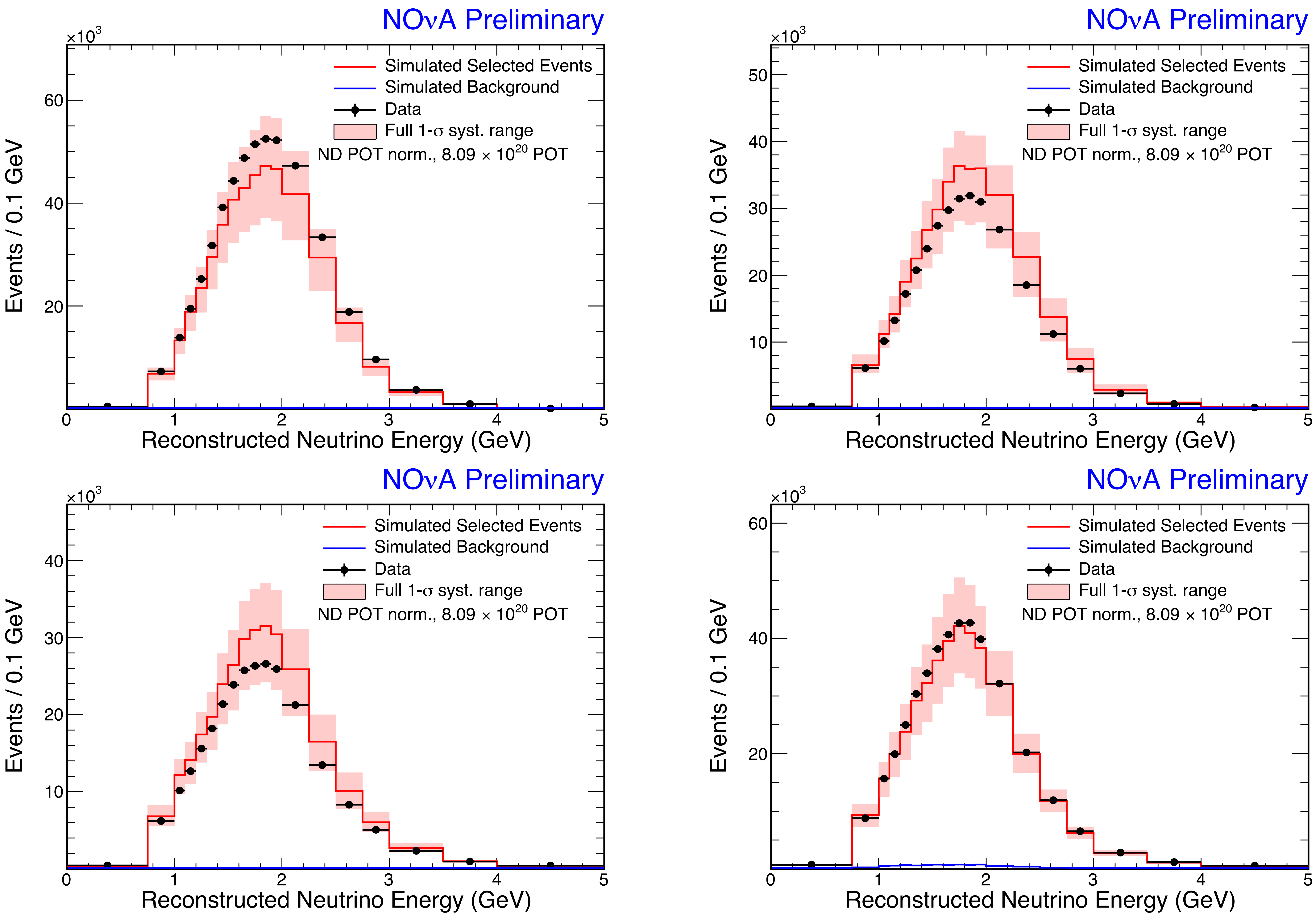


Resolution Binned Extrapolation

RPA shape uncertainty **extrapolation in one spectra.**

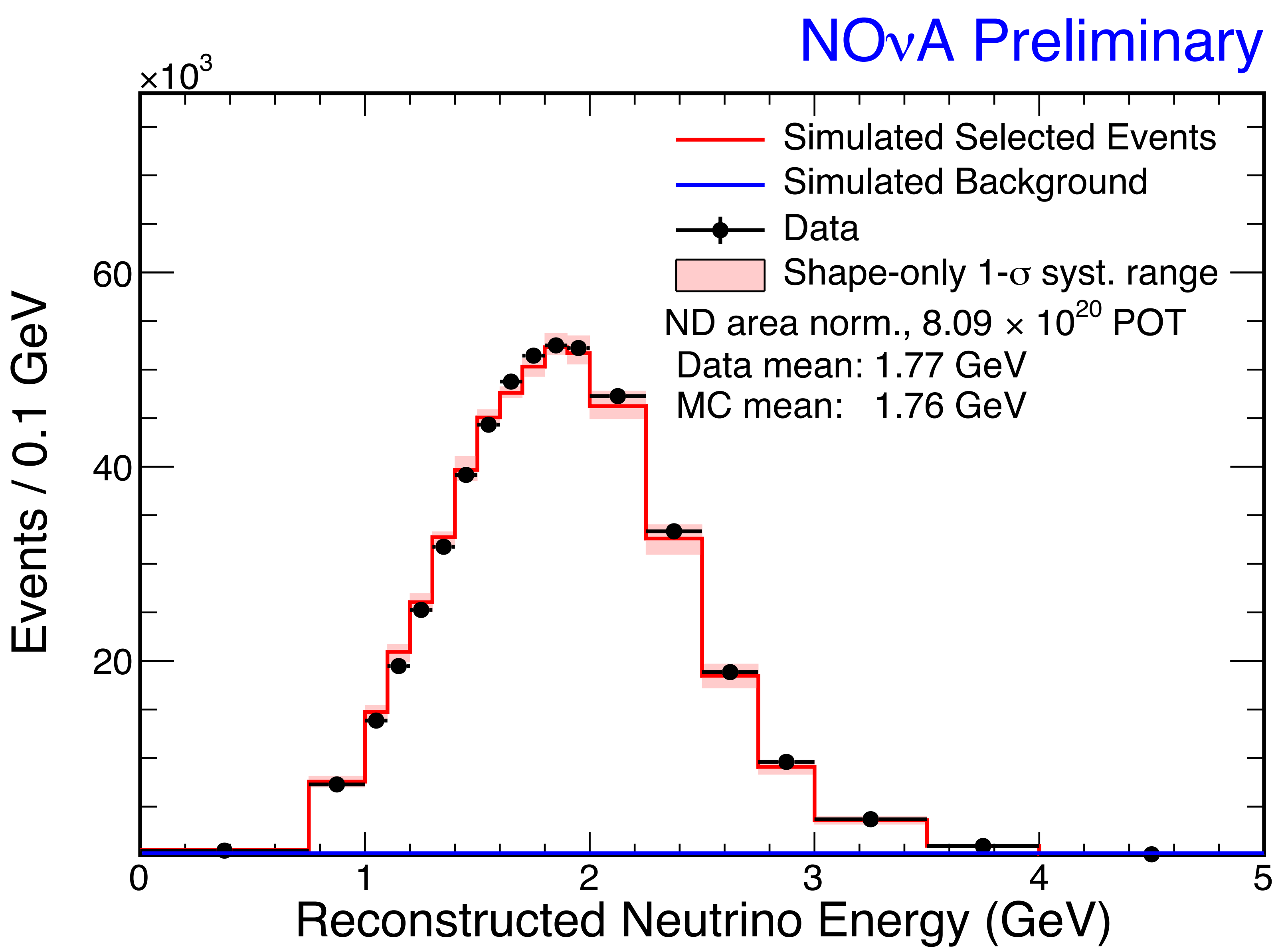


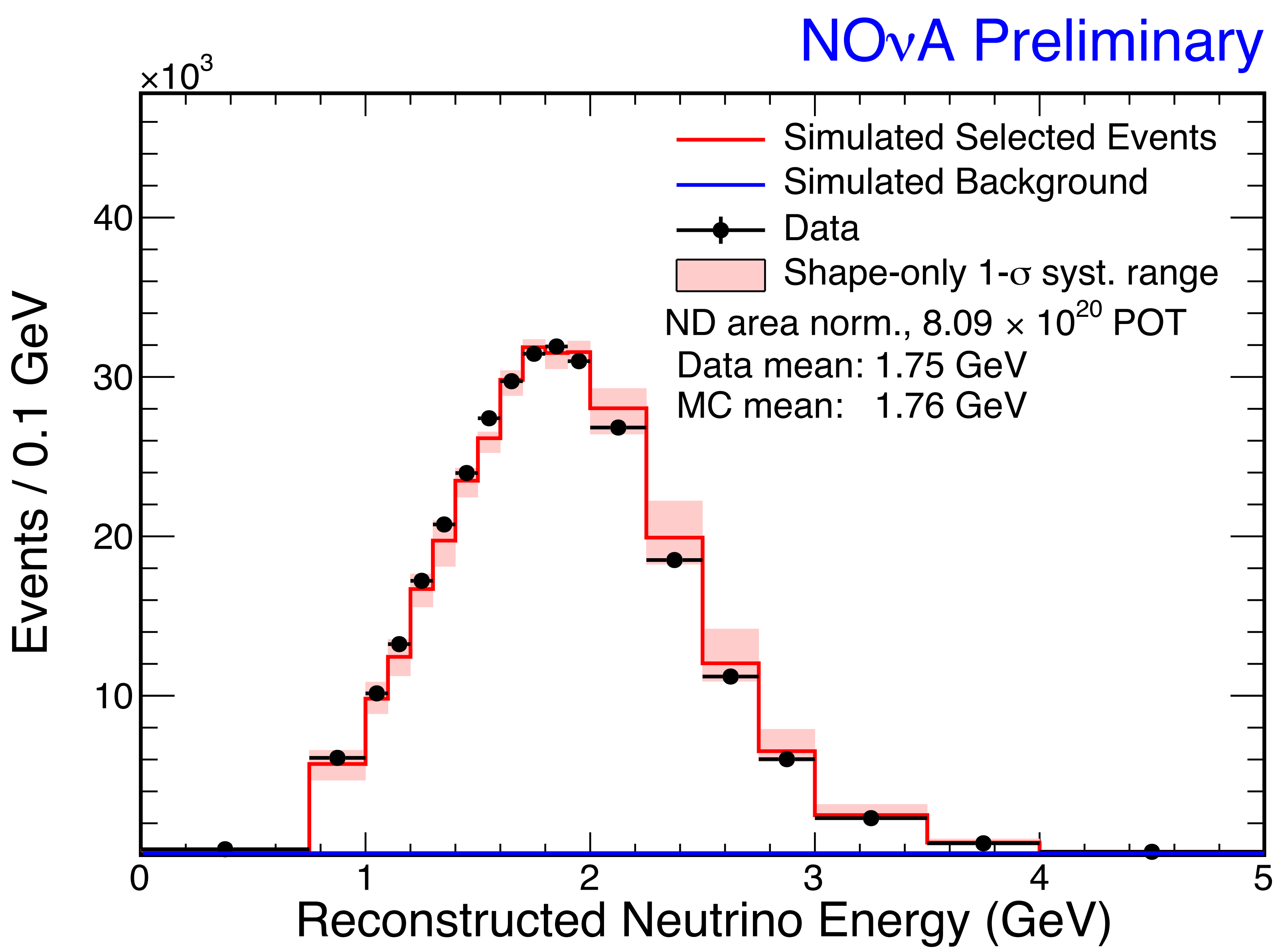
Resolution Binned Extrapolation

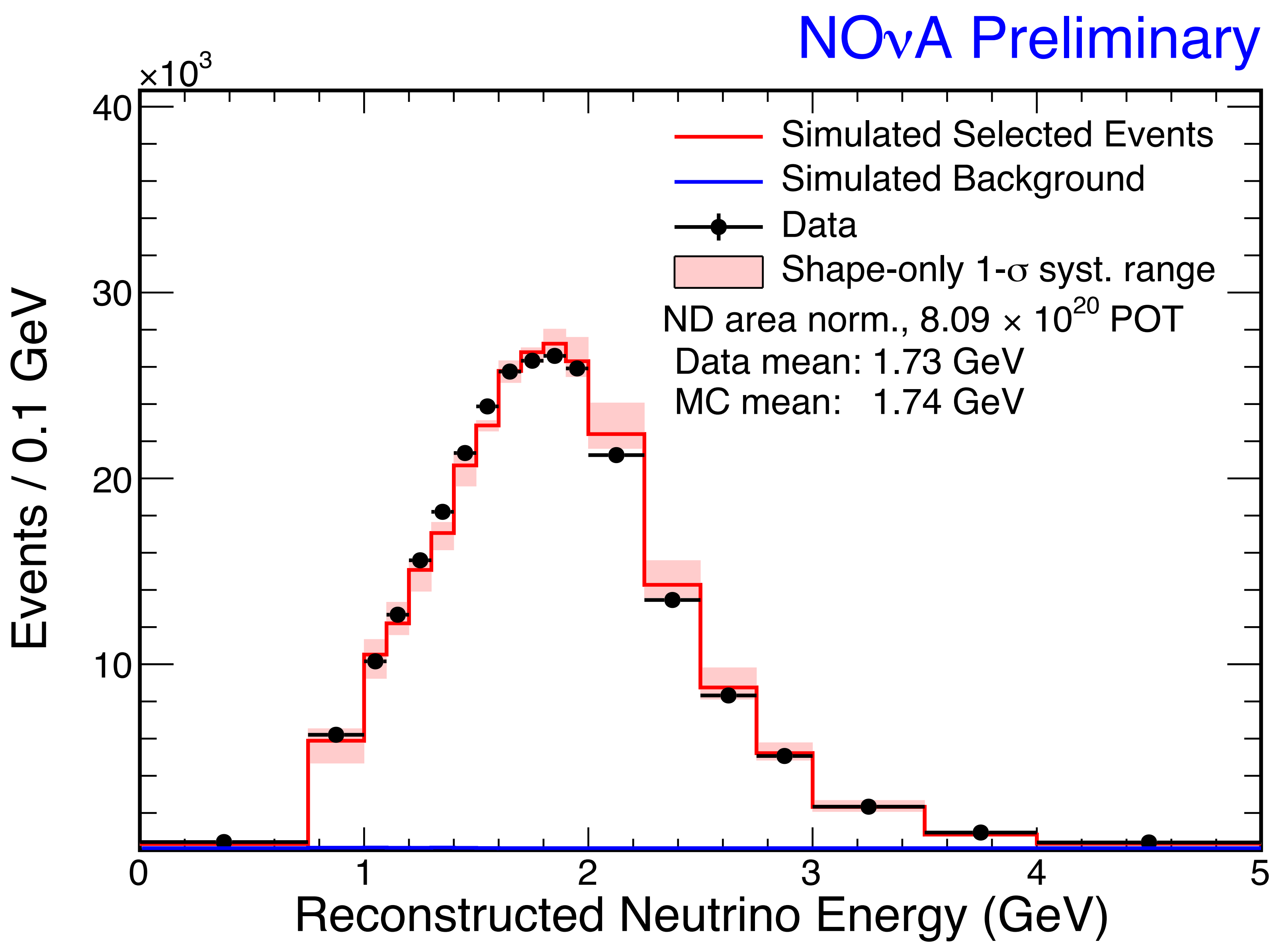


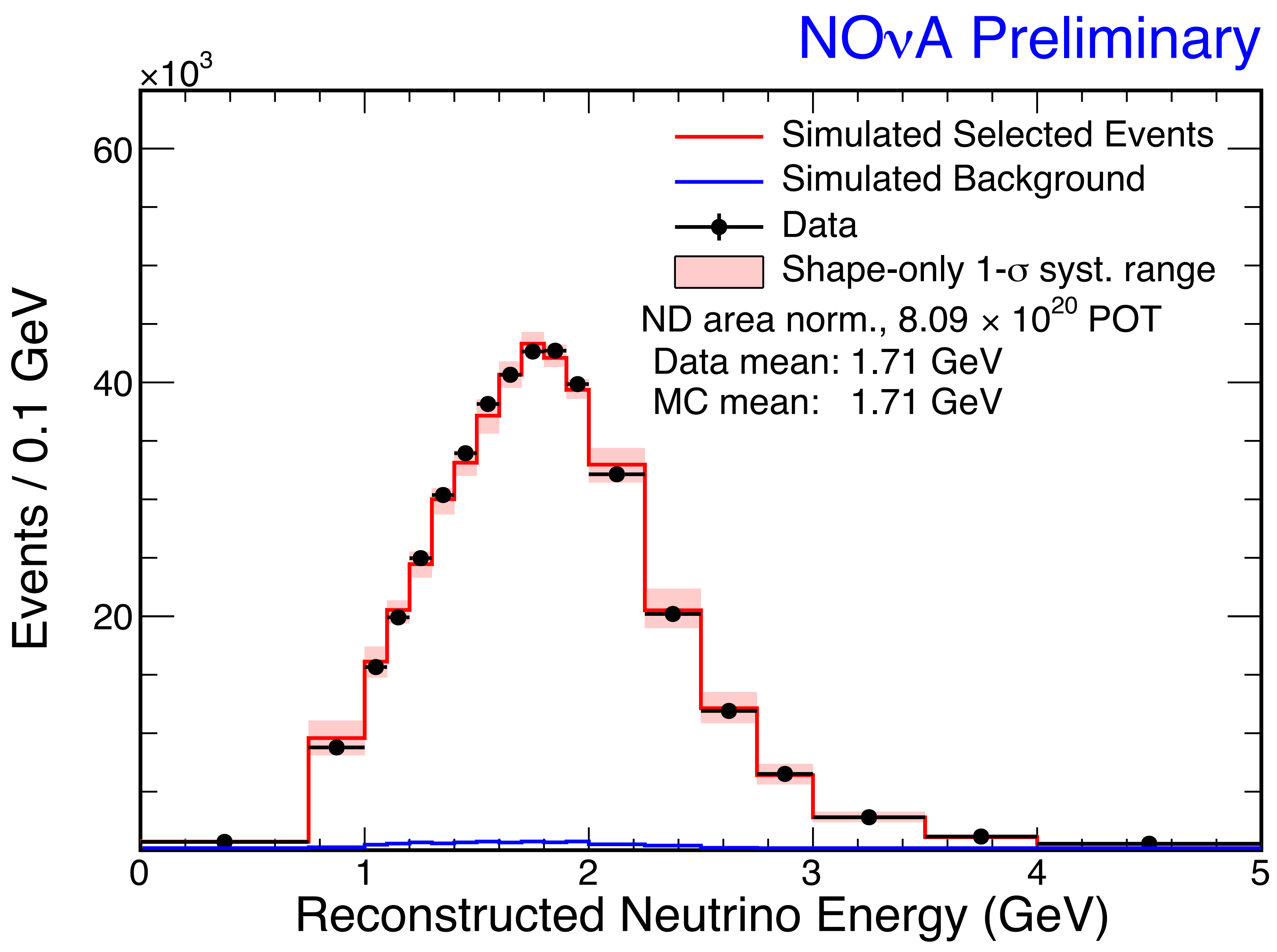
Resolution Binned Extrapolation

Area Normalized.



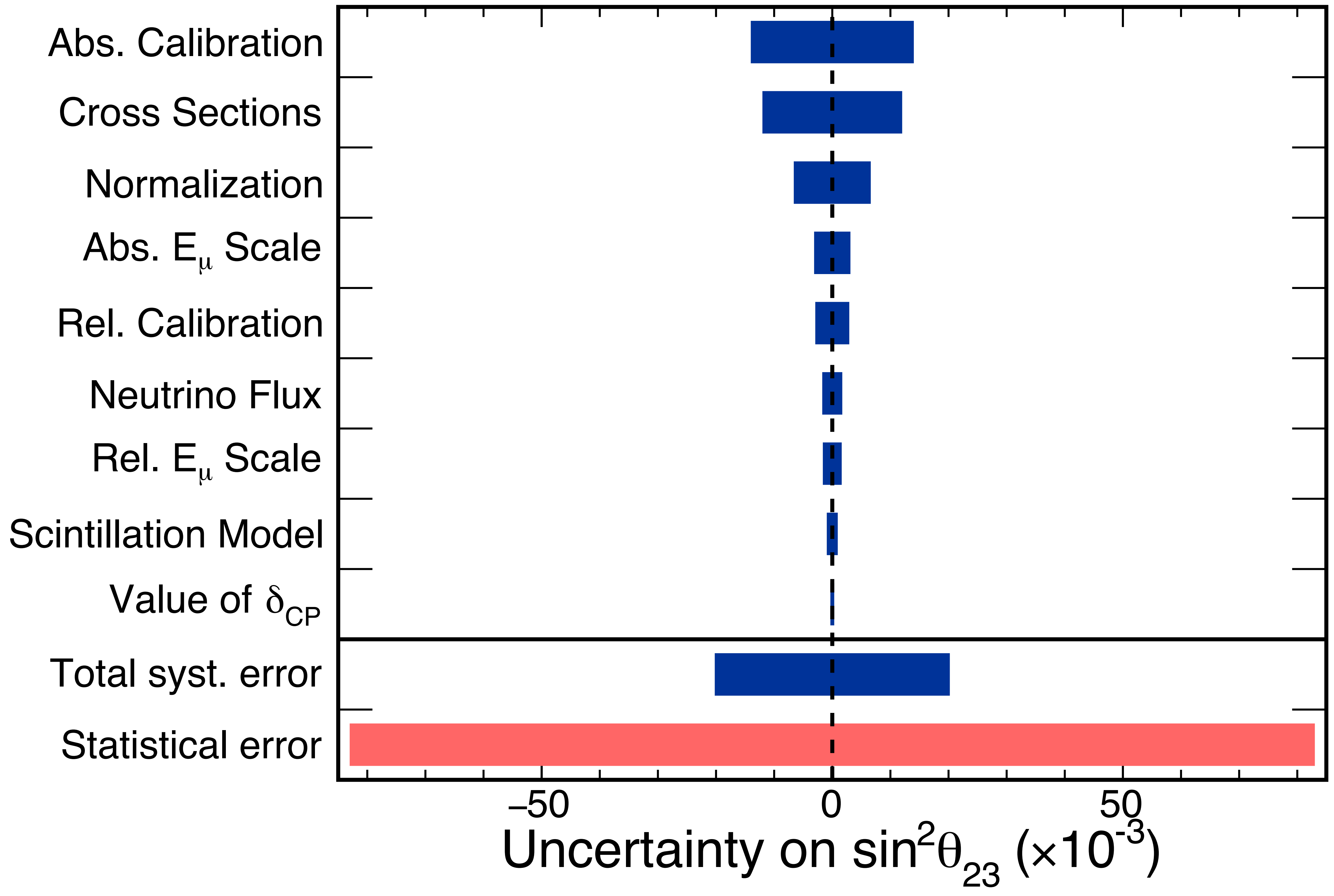


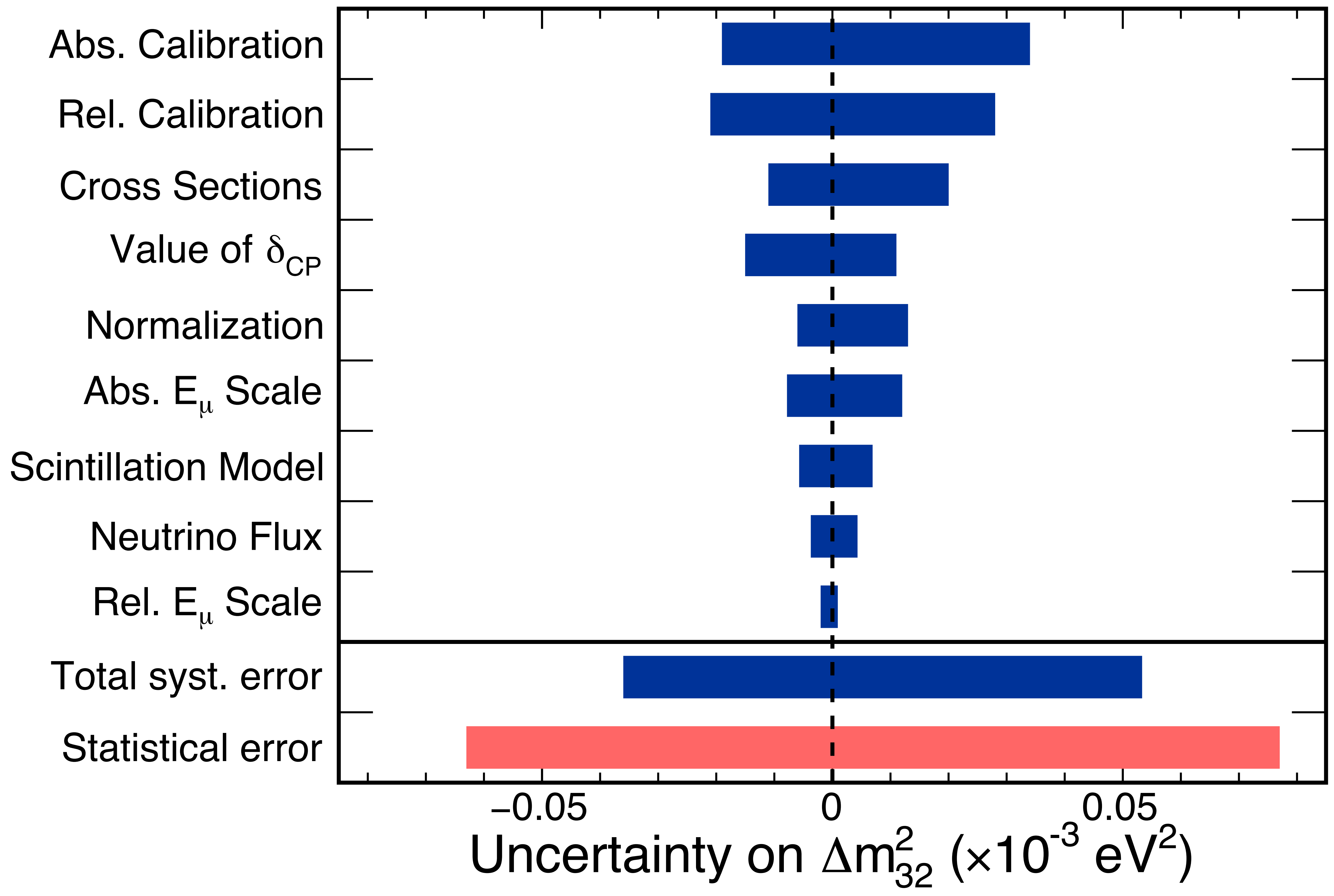




ν_μ Systematics

- Systematics were assessed by generating sets of shifted MC.
- Those shifted datasets were used instead of our nominal MC to assess the impact on our final result.





ν_μ FD Selected Sample

In the absence of oscillations we expect 763 events. **126 were observed.**

	Total Observed	Expectation at Best Fit	Total Background	Cosmic	Neutral Current	Other Beam
All Q Events	126	129	9.24	5.82	2.50	0.96

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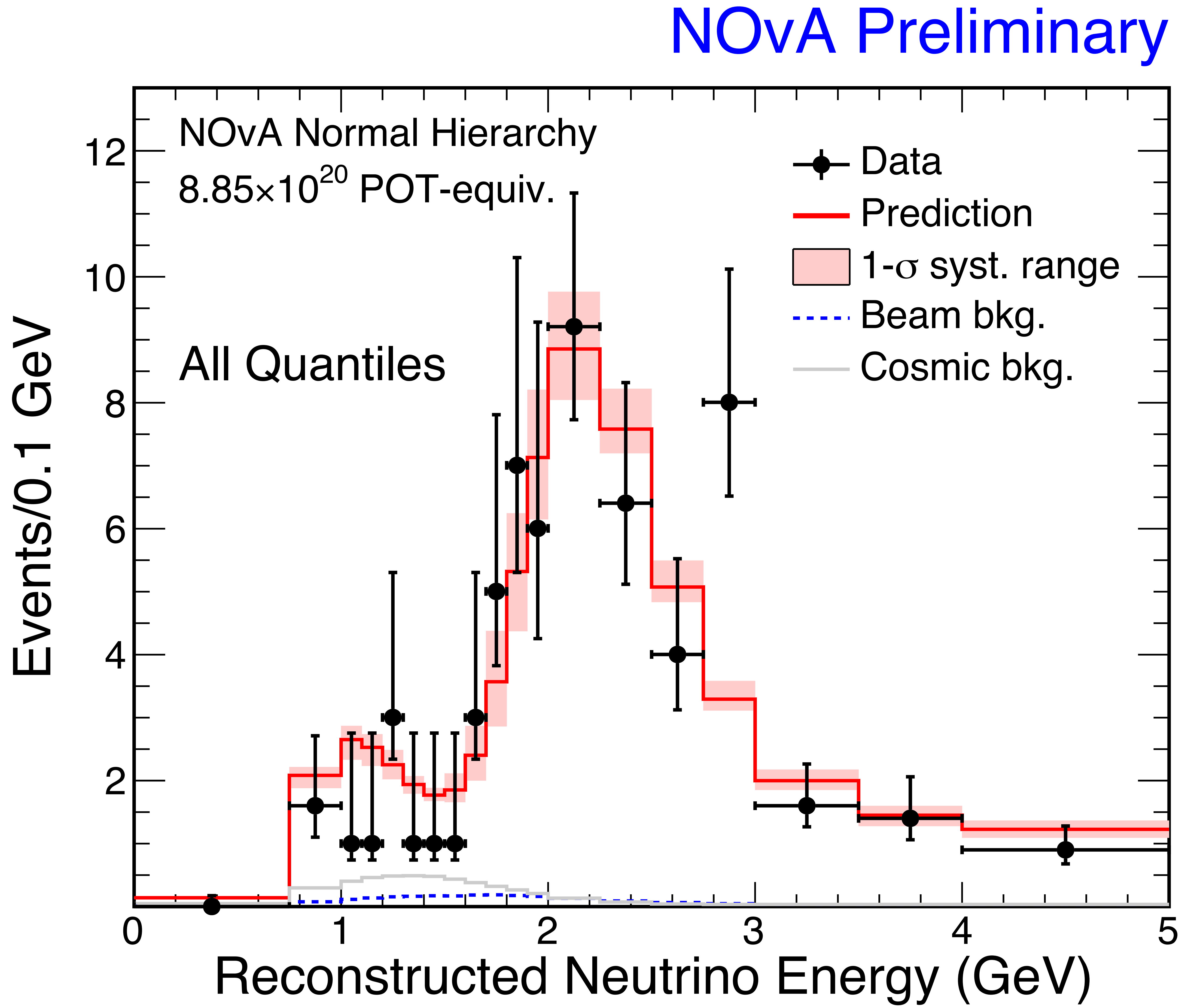
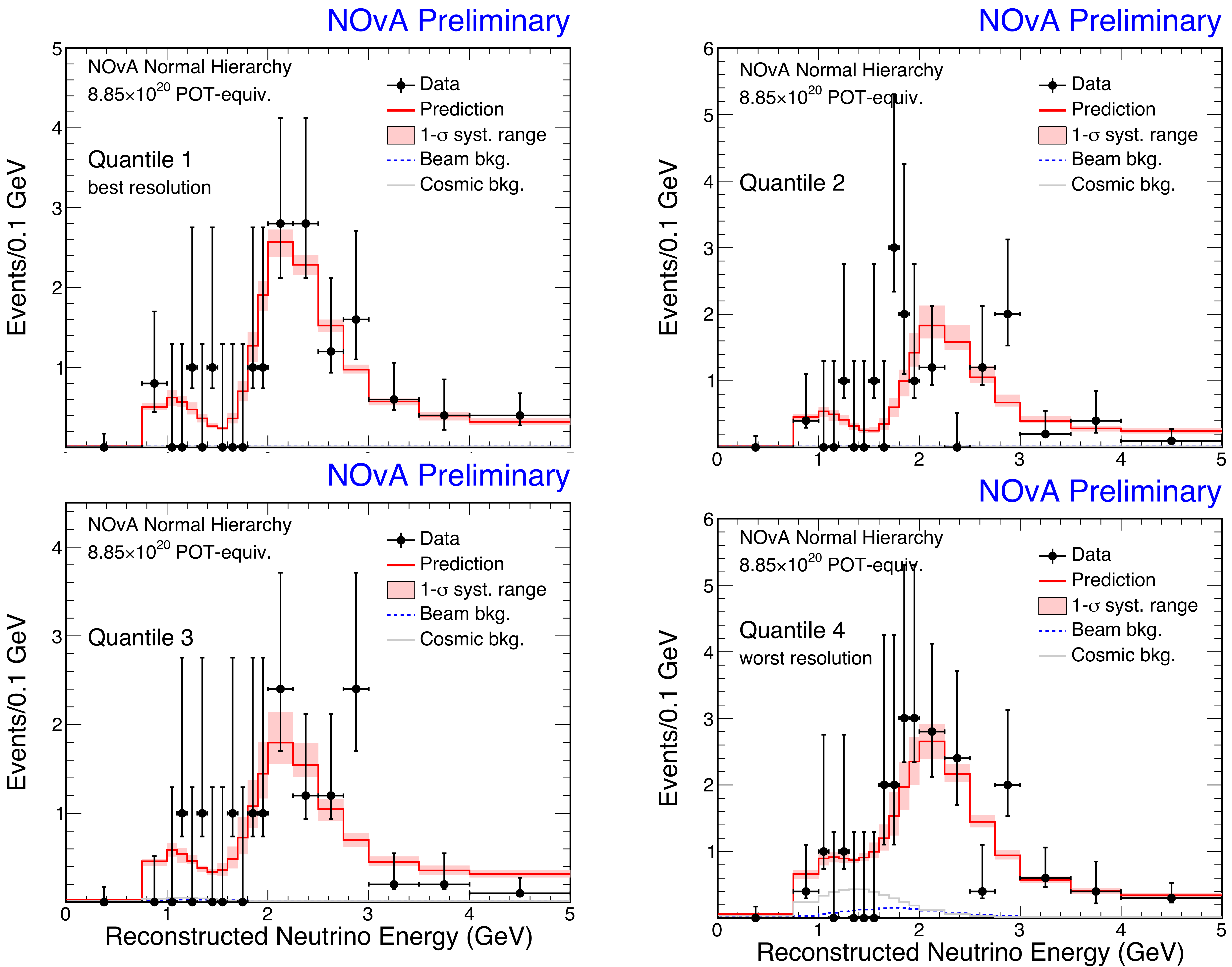


ν_μ FD Selected Sample

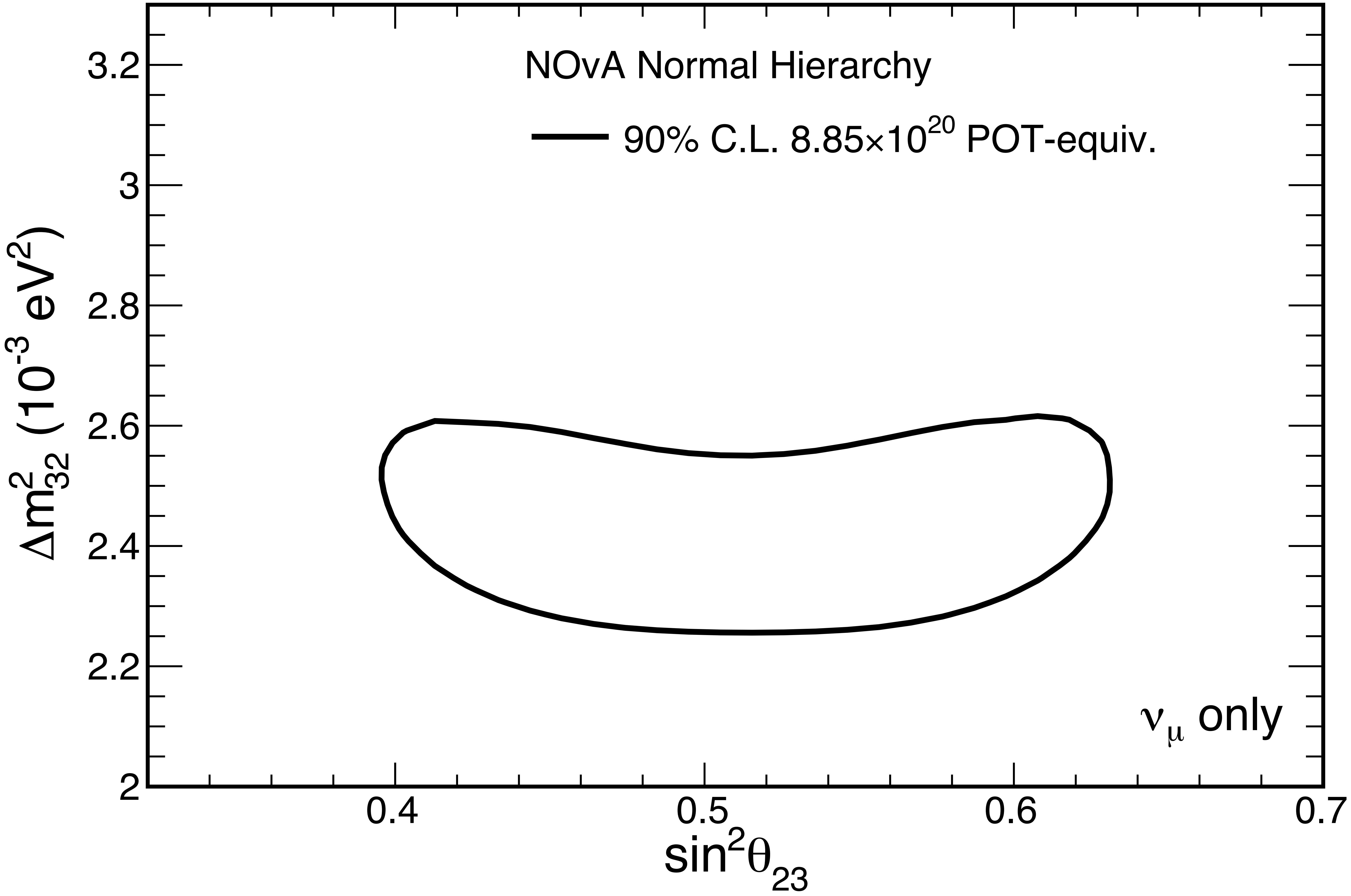
A. Radovic, JETP January 2018



ν_μ Result

- Full joint fit with appearance analysis. Feldman Cousins corrections in 2D & 1D limits.
- All systematics, oscillation pull terms shared.
- Constrain θ_{13} using world average from PDG, $\sin^2 2\theta_{13} = 0.082$

NOvA Preliminary



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Best fit:

$\Delta m^2_{32} =$
$2.444^{+0.079}_{-0.077} \times 10^{-3}\ \mathrm{eV}^2$

UO preferred at 0.2σ

$\sin^2\theta_{23} =$

UO: $0.558^{+0.041}_{-0.033}$

LO: $0.475^{+0.036}_{-0.044}$

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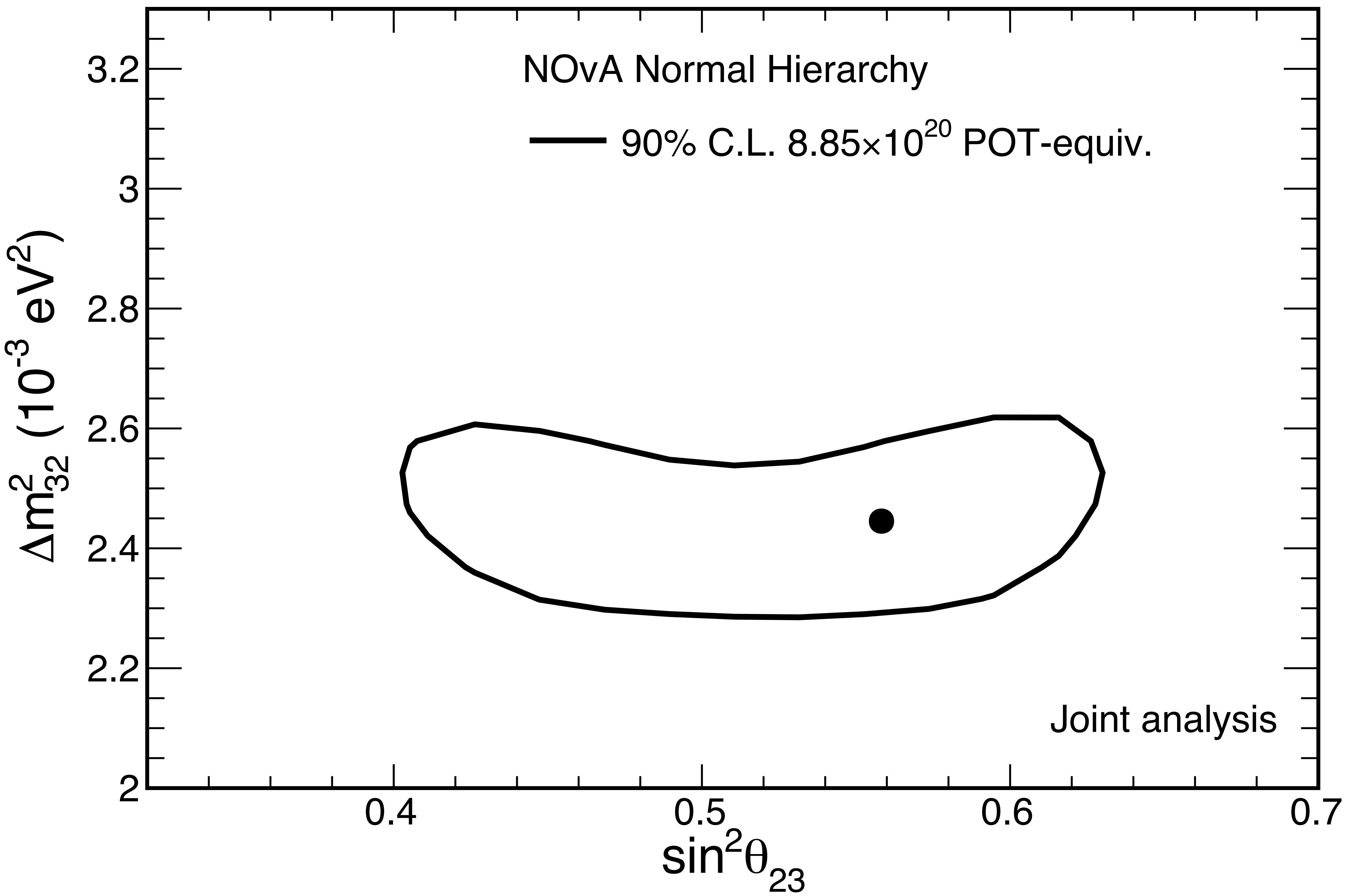

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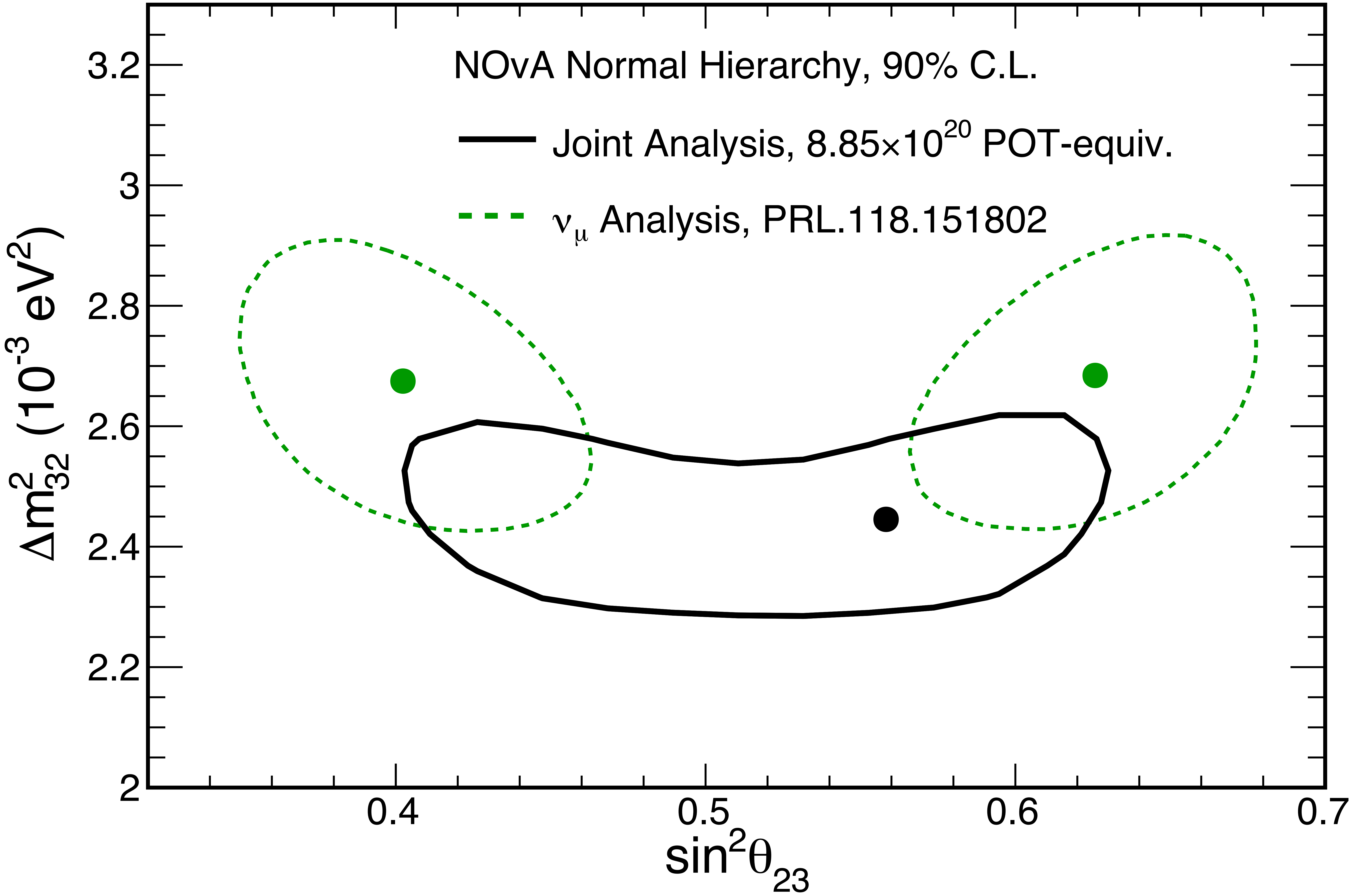

ν_μ Result- Comparison To Previous Result

Our previous result*:
2.6σ

New simulation & Calibration:
~1.8σ

New selection and analysis:
~0.5σ

Full dataset:
~0.4σ

Full dataset*:
0.8σ

Our rejection of maximal mixing has moved from 2.6σ to 0.8σ. This change in the character of our result comes from a few key changes which I'll break down below.

Driven by updates to energy response model. Drop to 2.3σ expected due to new energy resolution. Additionally we have a <70 MeV> shift in our hadronic energy response. This energy shift would be expected to move 0.5 events out of the "dip" region. However it instead pushes 3 "dip" events past a bin boundary.

For combined analysis changes 5% of pseudo-experiments in a MC study had this size shift or larger. This probability is driven by a low expected overlap in background events, and to second order the addition of resolution bins.

New, 2.8×10^{20} POT, data prefers maximal mixing.

*Feldman-cousins corrected significance.

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Atmospheric Mixing and World Constraints

- Consistent with world expectation.
- Competitive measurement of Δm^2_{32}.

Best fit:

Δm^2_{32} =

$2.444^{+0.079}_{-0.077} \times 10^{-3}\ eV^2$

UO preferred at 0.2σ

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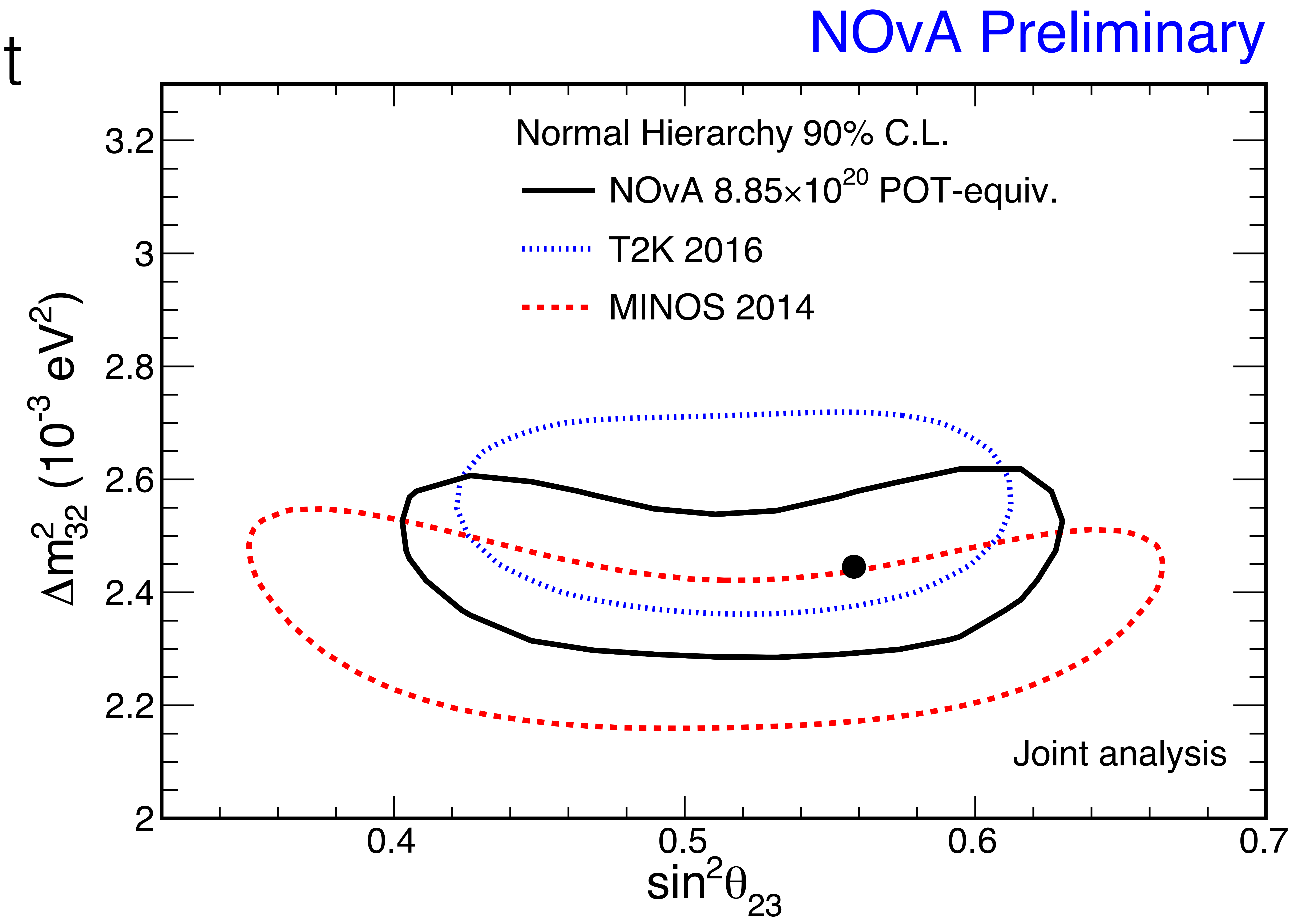
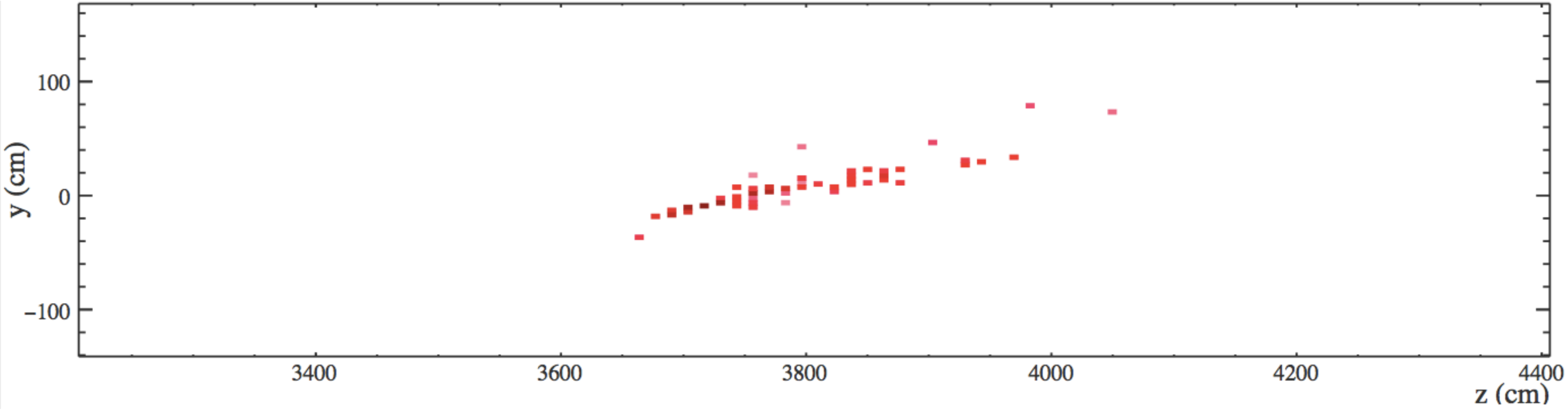


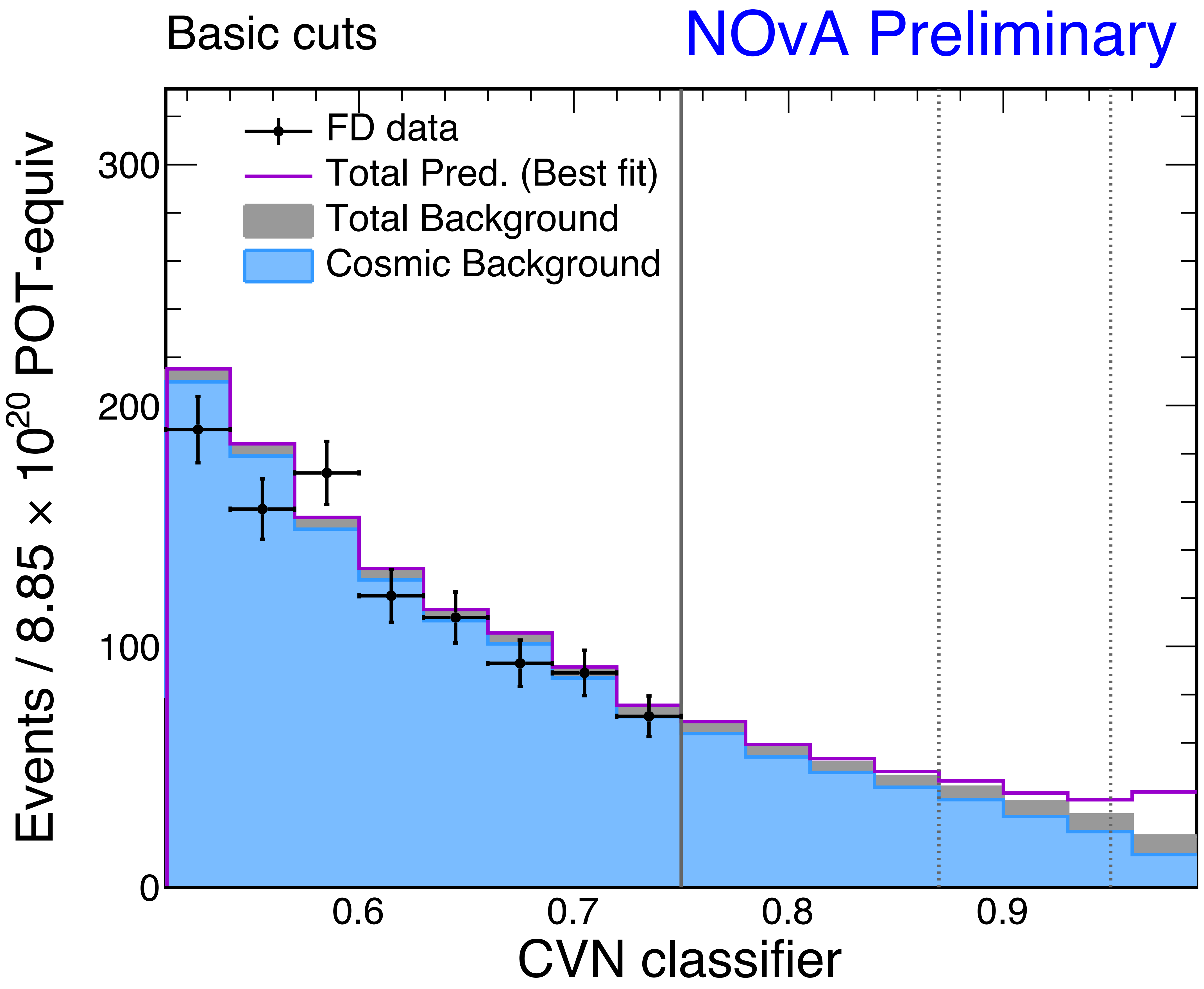
ν_e Appearance

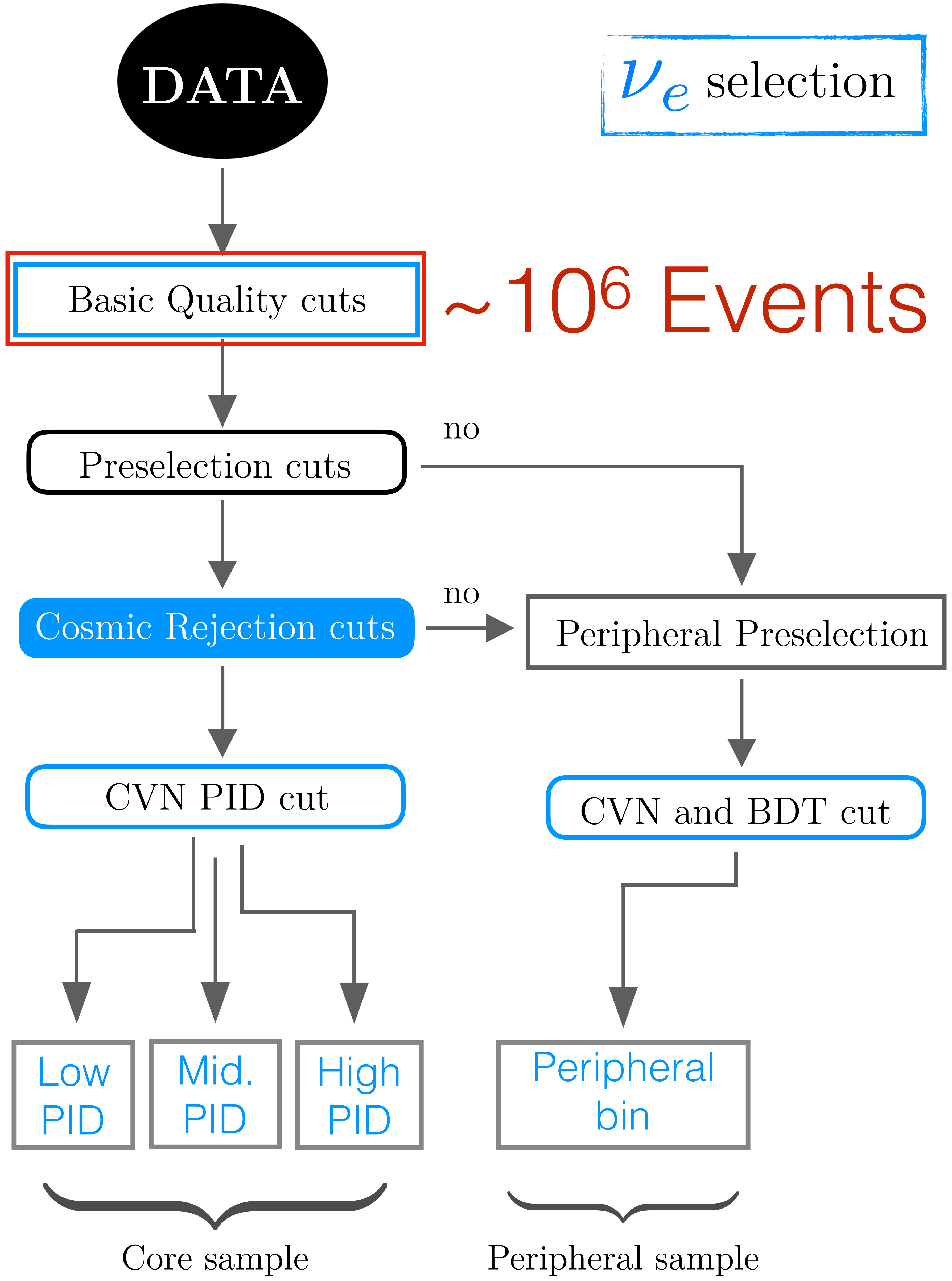
1. Measure ND and FD ν_e and ν_μ Selected Spectra
2. Break down ND ν_e selected events to separately extrapolate background components.
3. Extrapolate ND ν_μ selected events estimate signal at the FD. Use FD data from outside of the beam spill to estimate cosmic backgrounds.
4. Compare measured FD to expectation.



ν_e Selection

Optimized to maximally exploit the power of our our CVN ID. Select down to low PID values to recover as many signal events as possible. Binning in PID to retain the full power of the high purity subsample of events.





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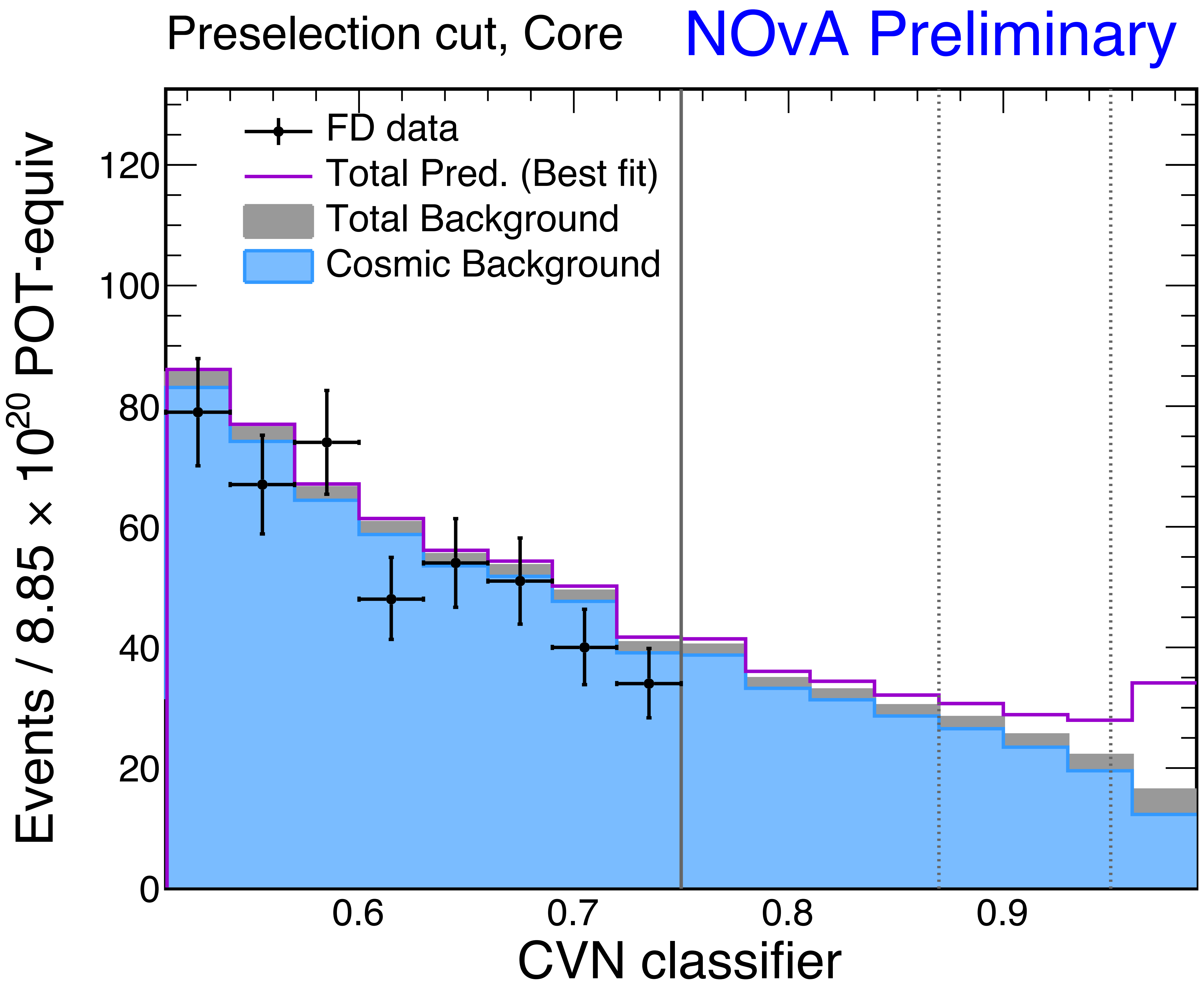

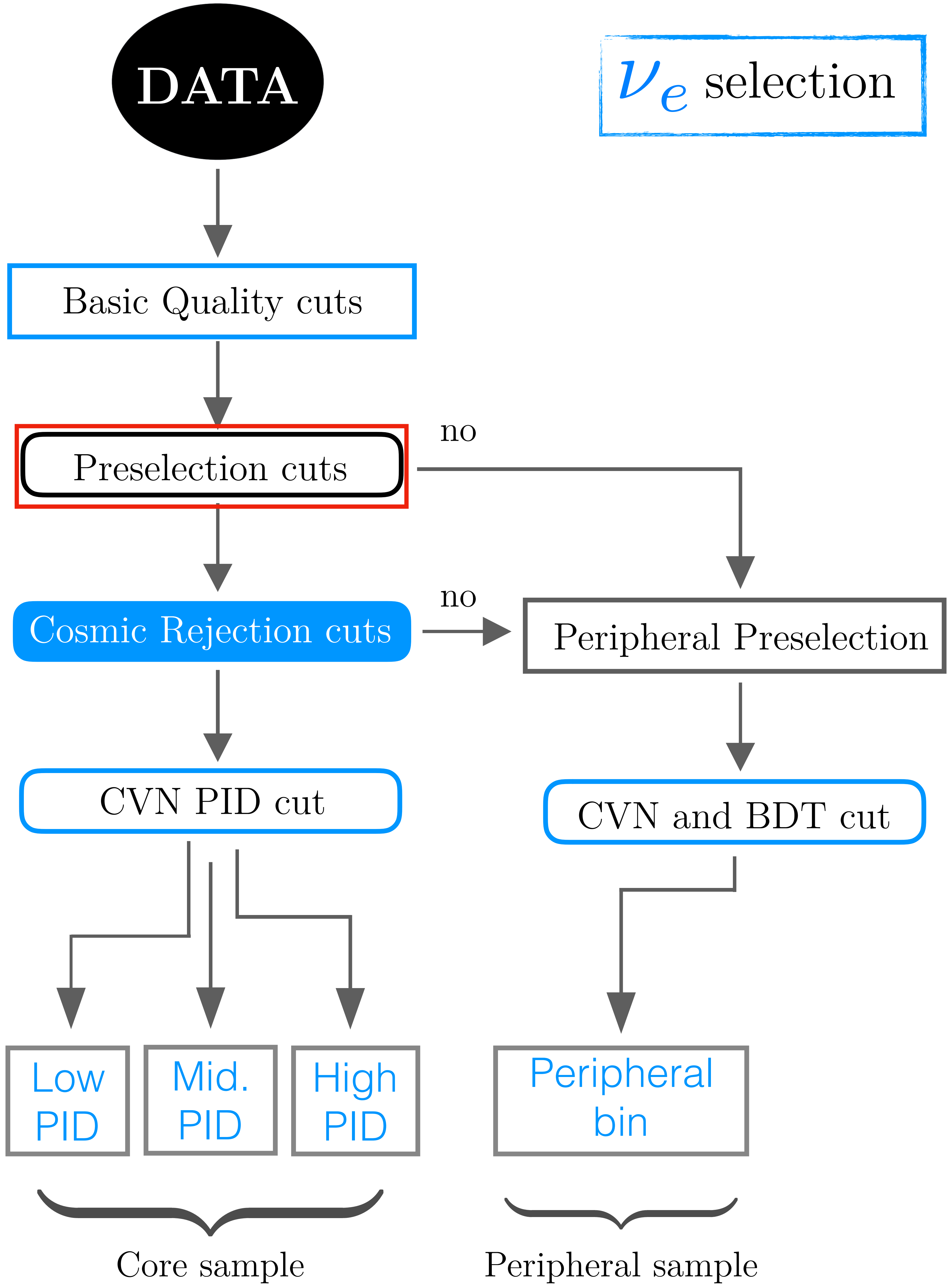

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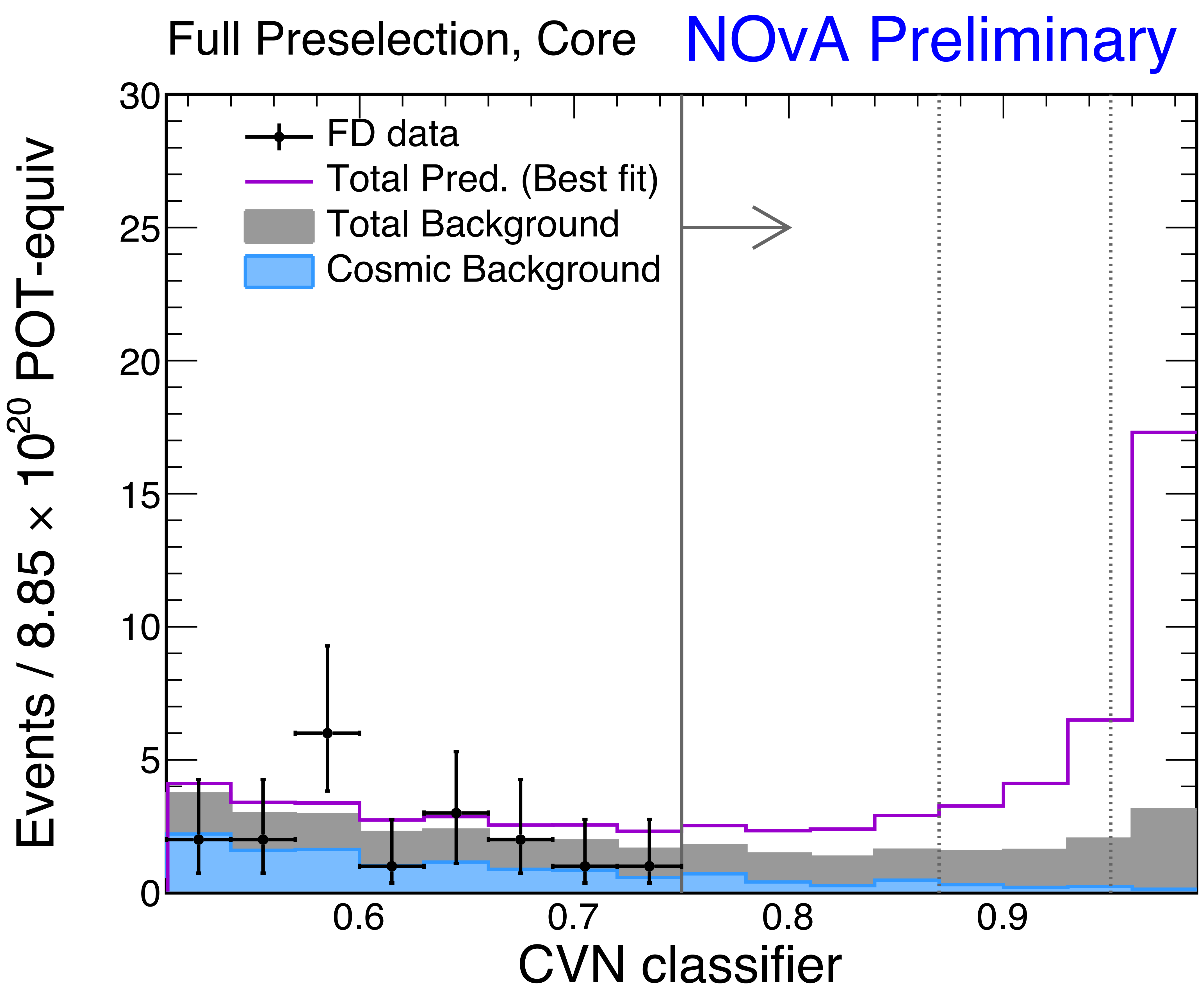
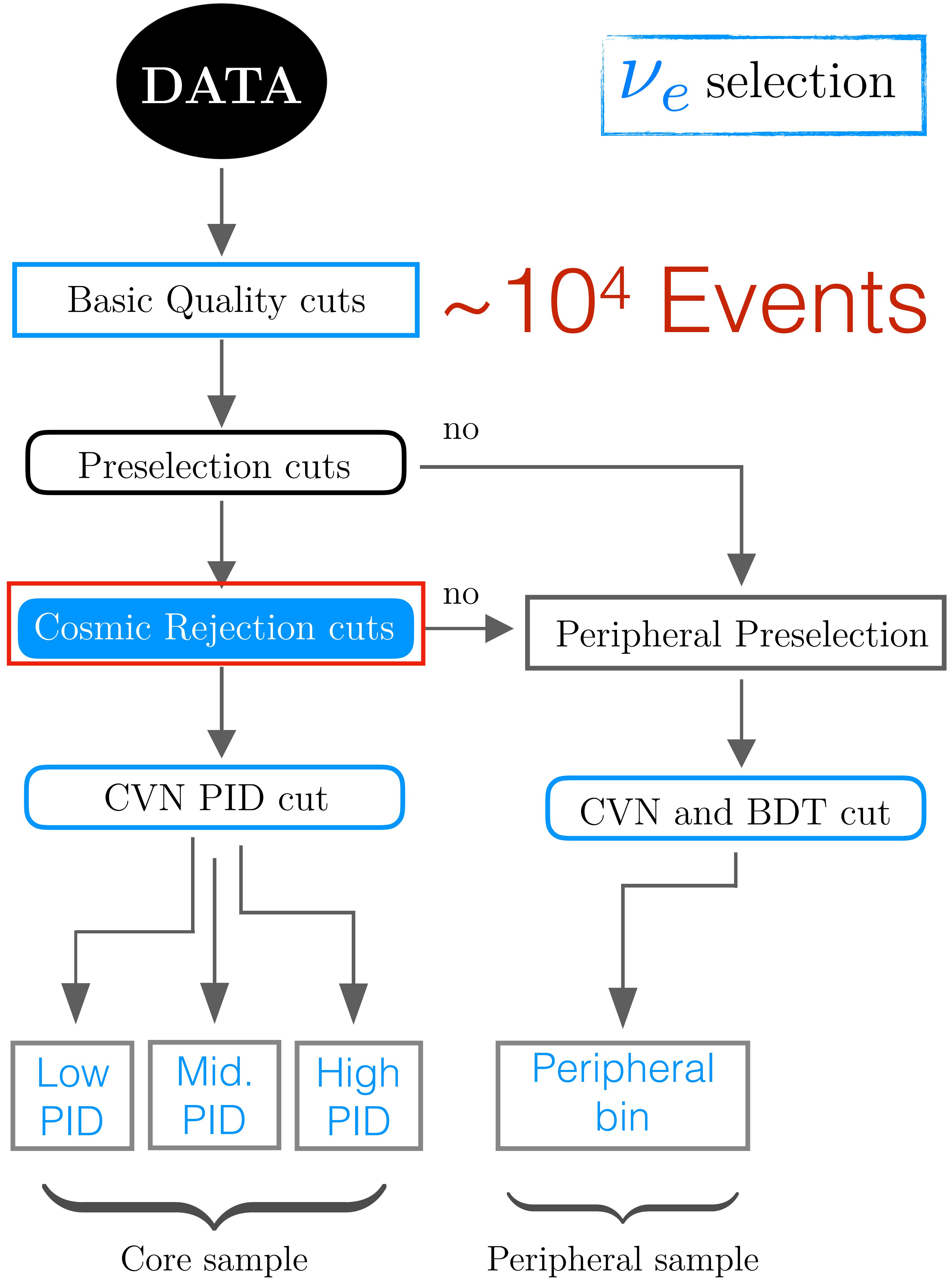
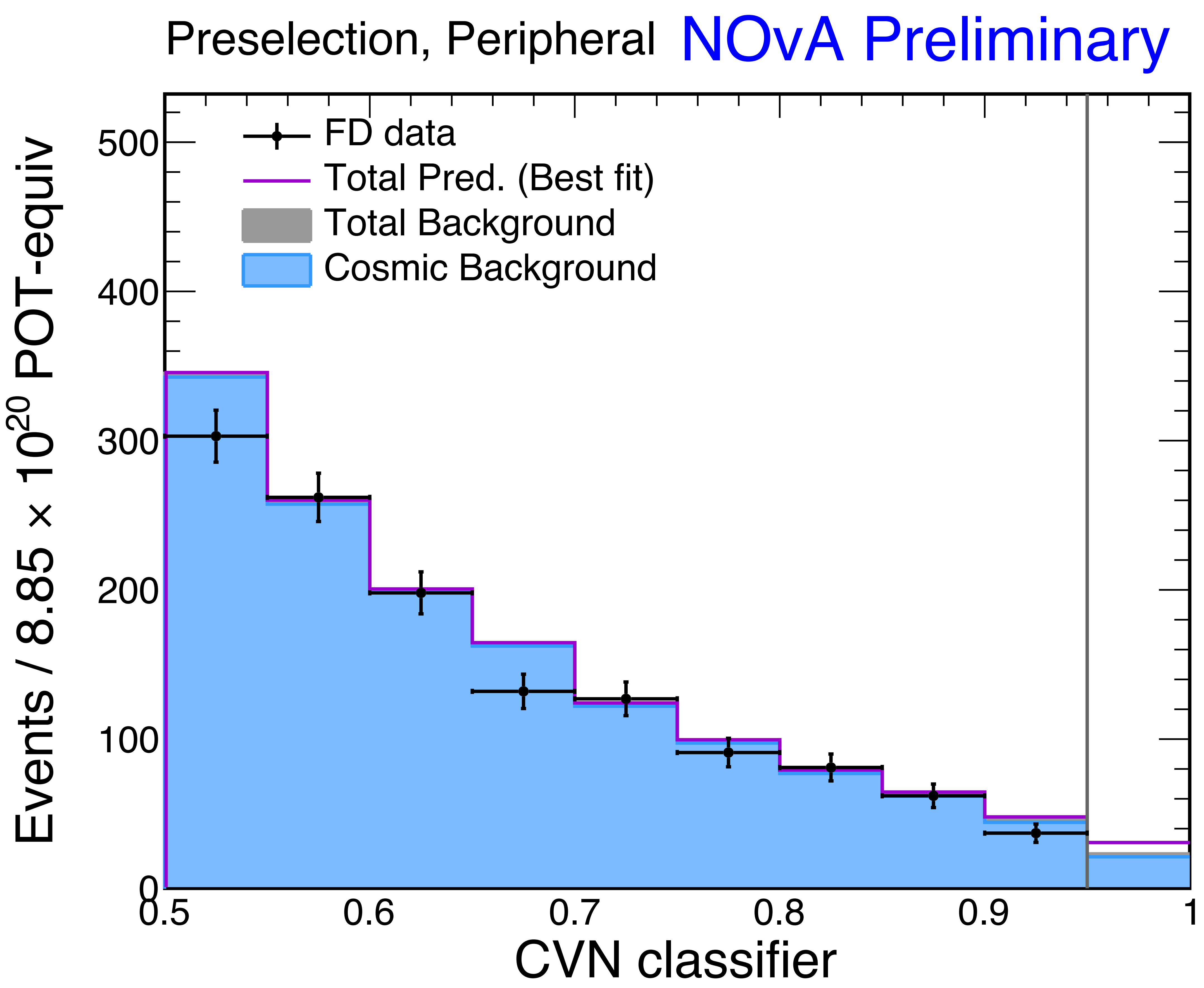
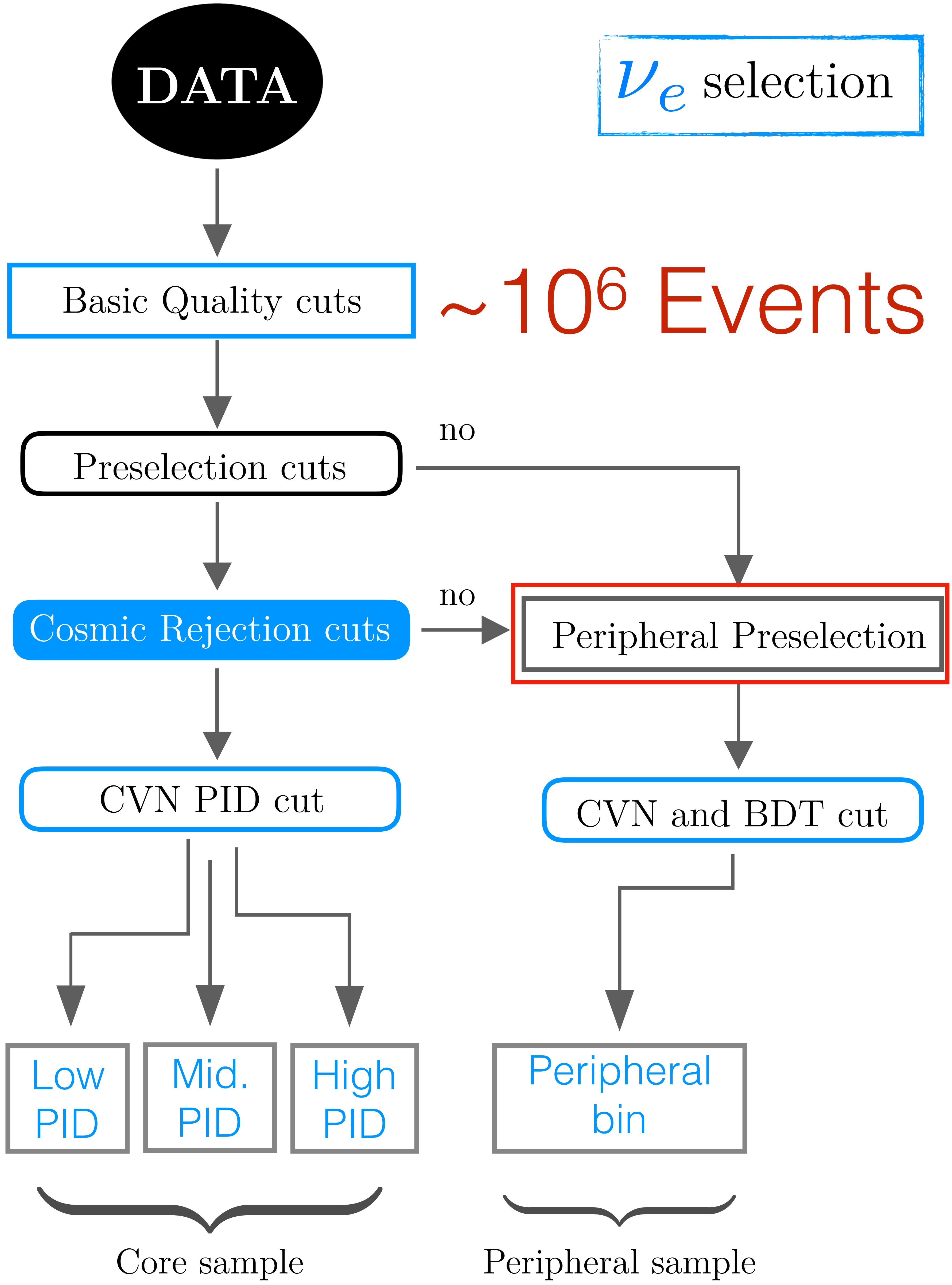




ν_e Selection

Harsh cosmic rejection cuts also reject some signal events. The addition of a new cosmic rejection BDT and a tight cut on CVN allow us to reclaim some of those events.





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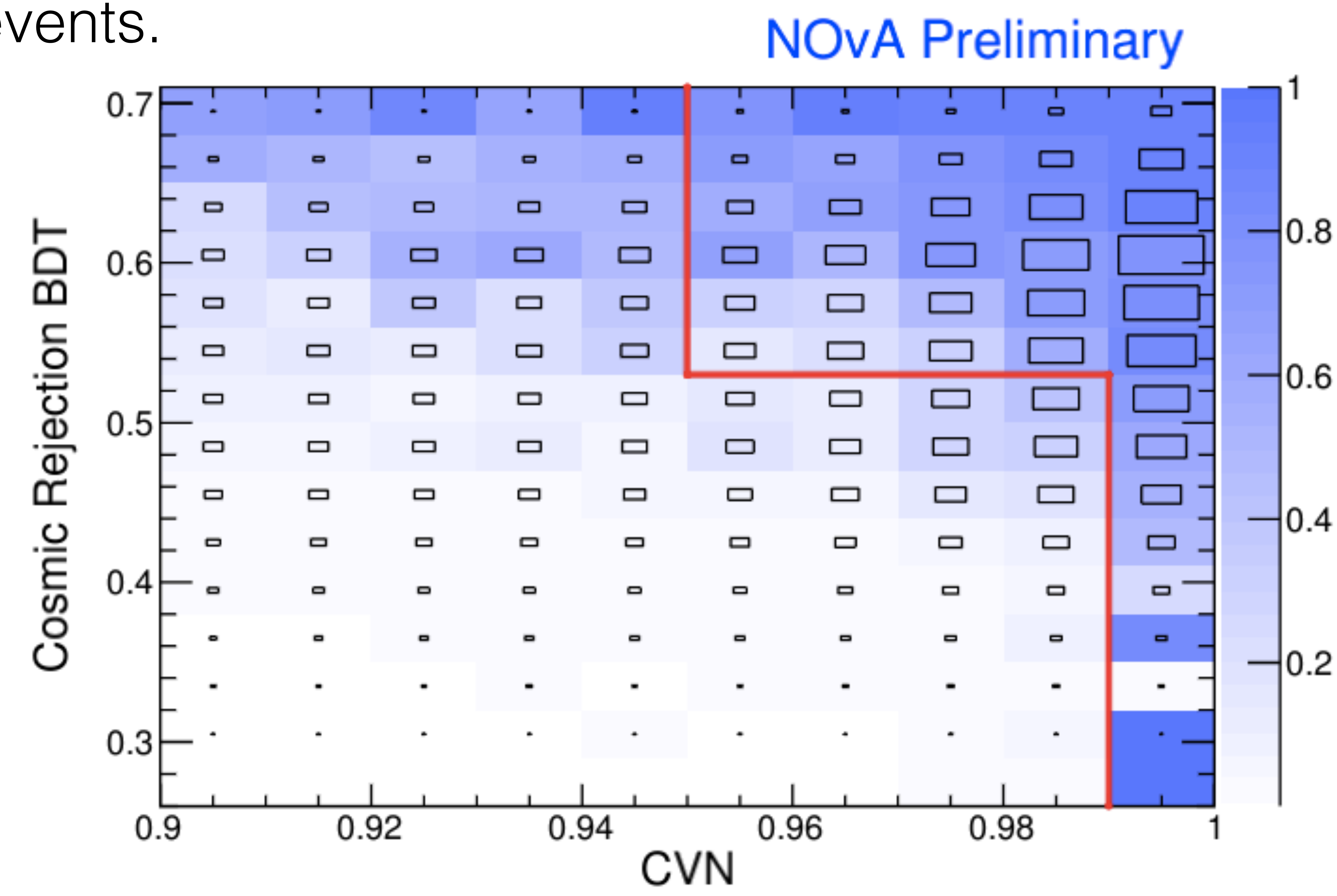

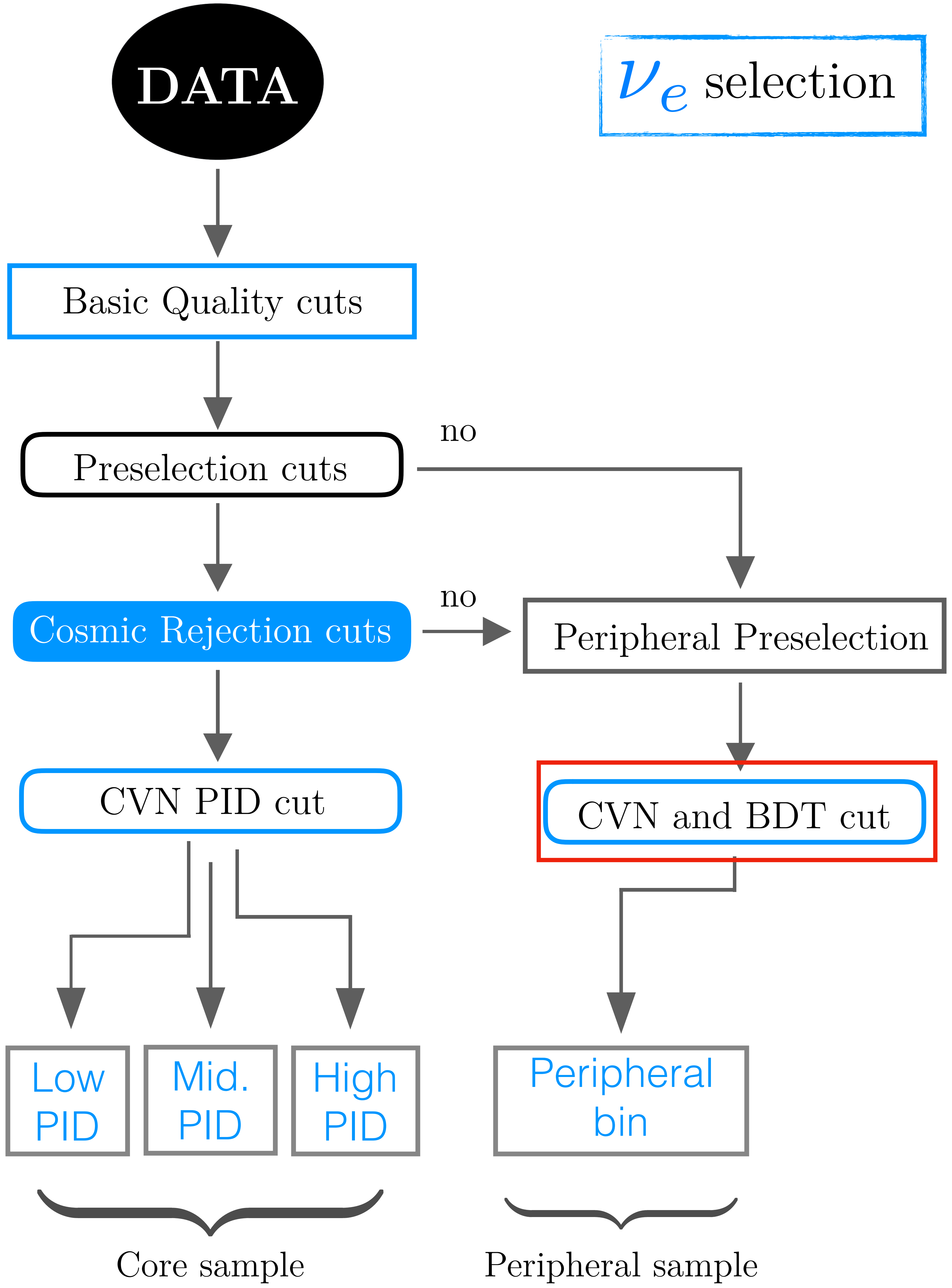

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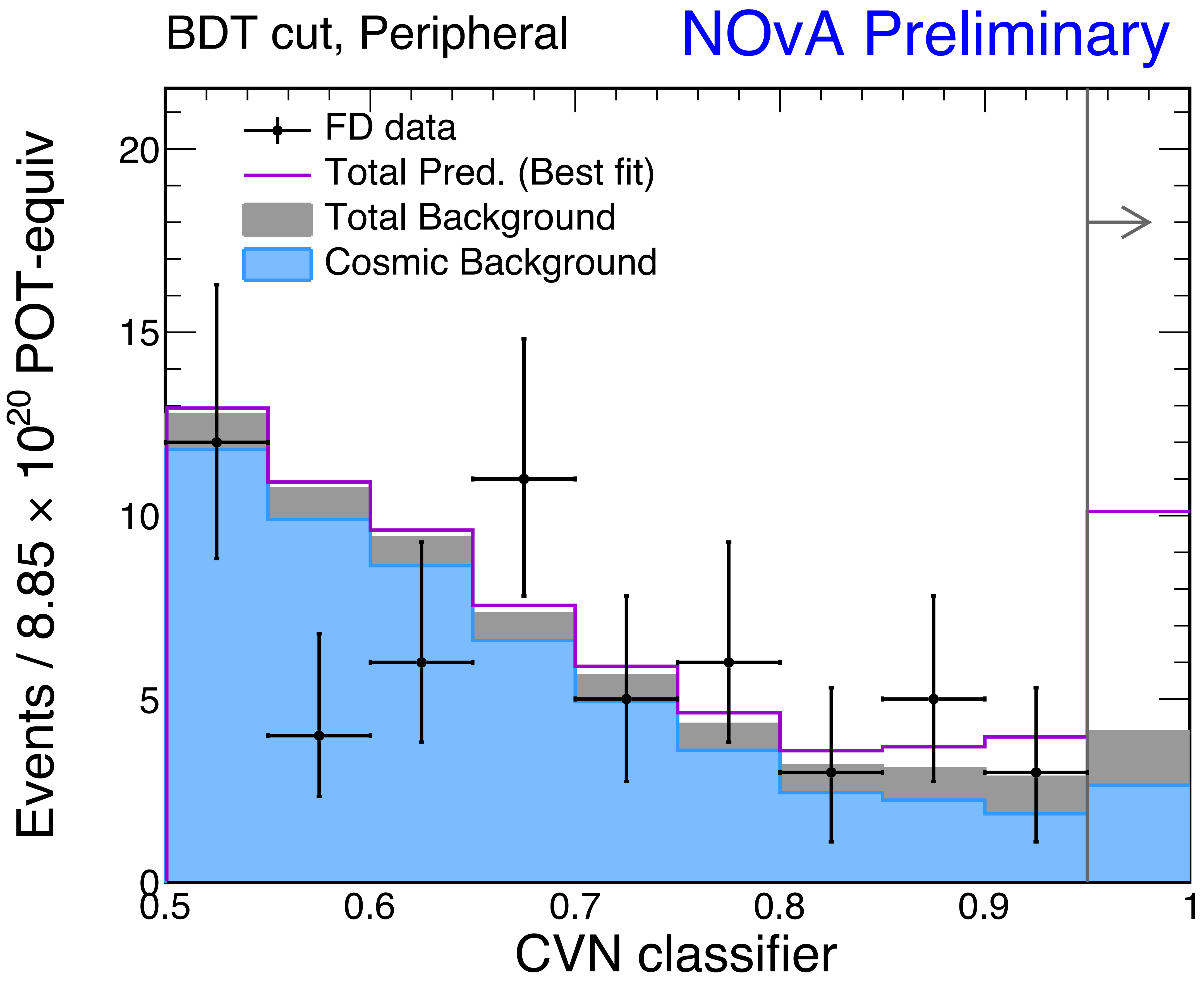

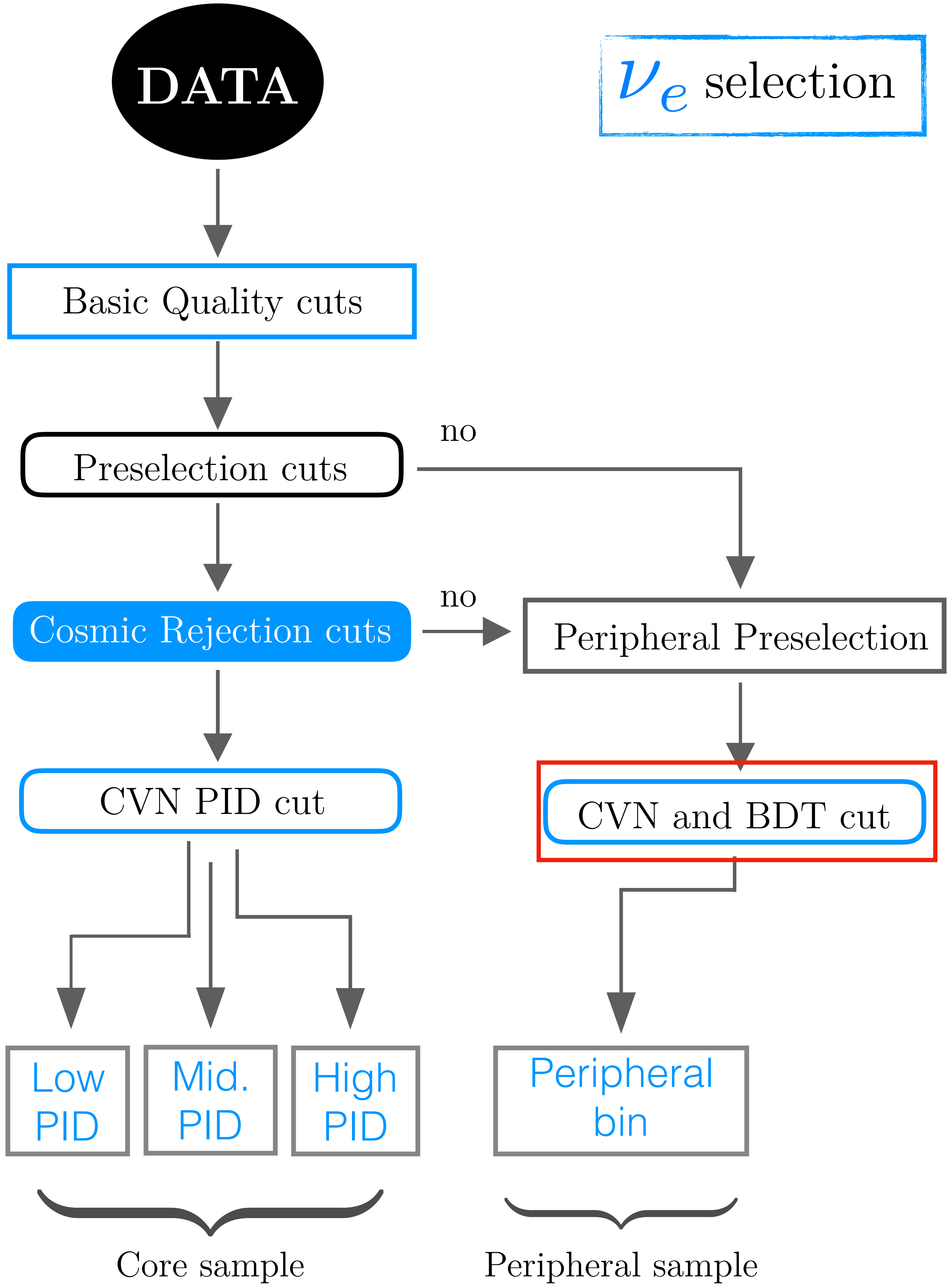

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 A. Radovic, JETP January 2018

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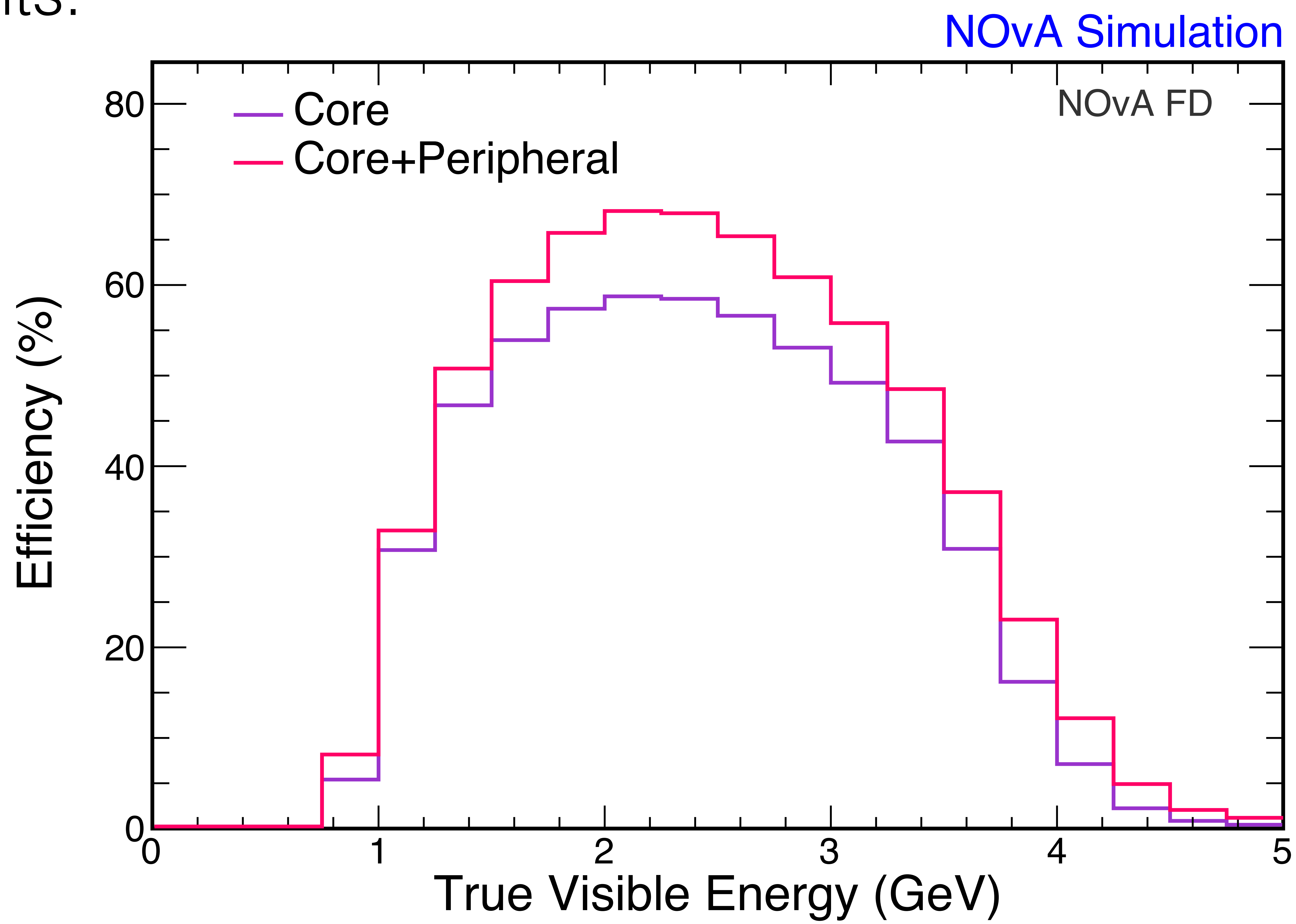

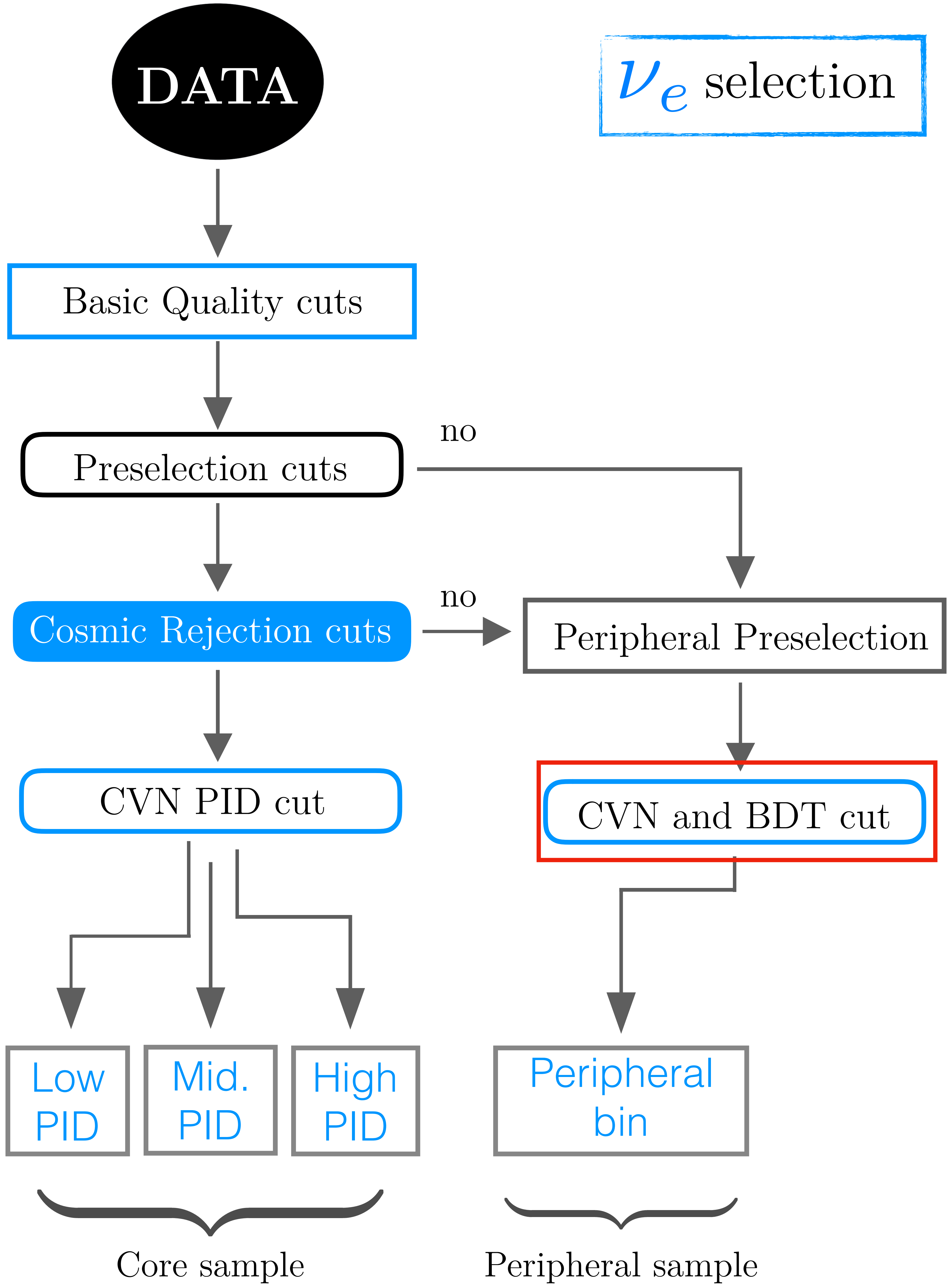

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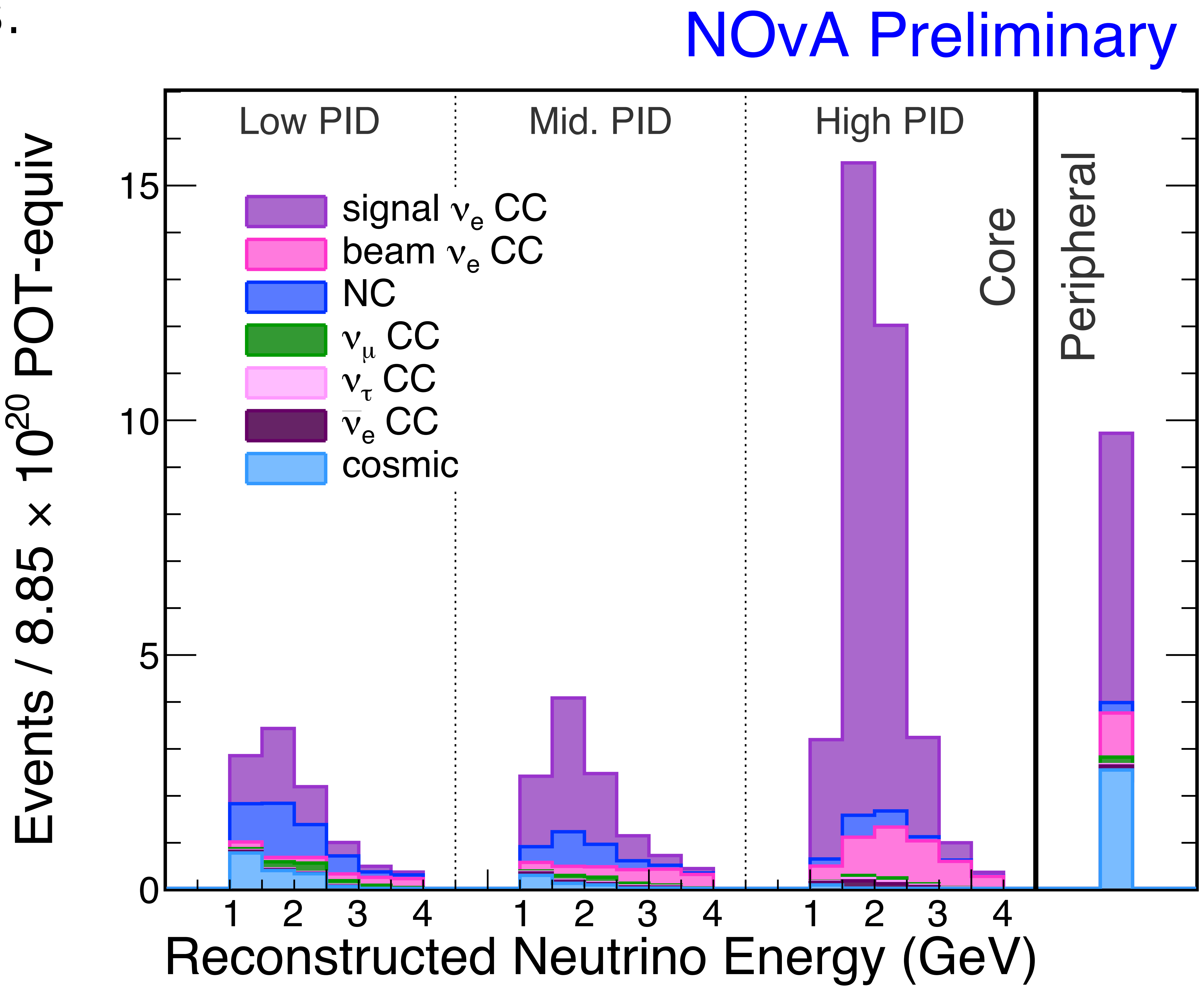
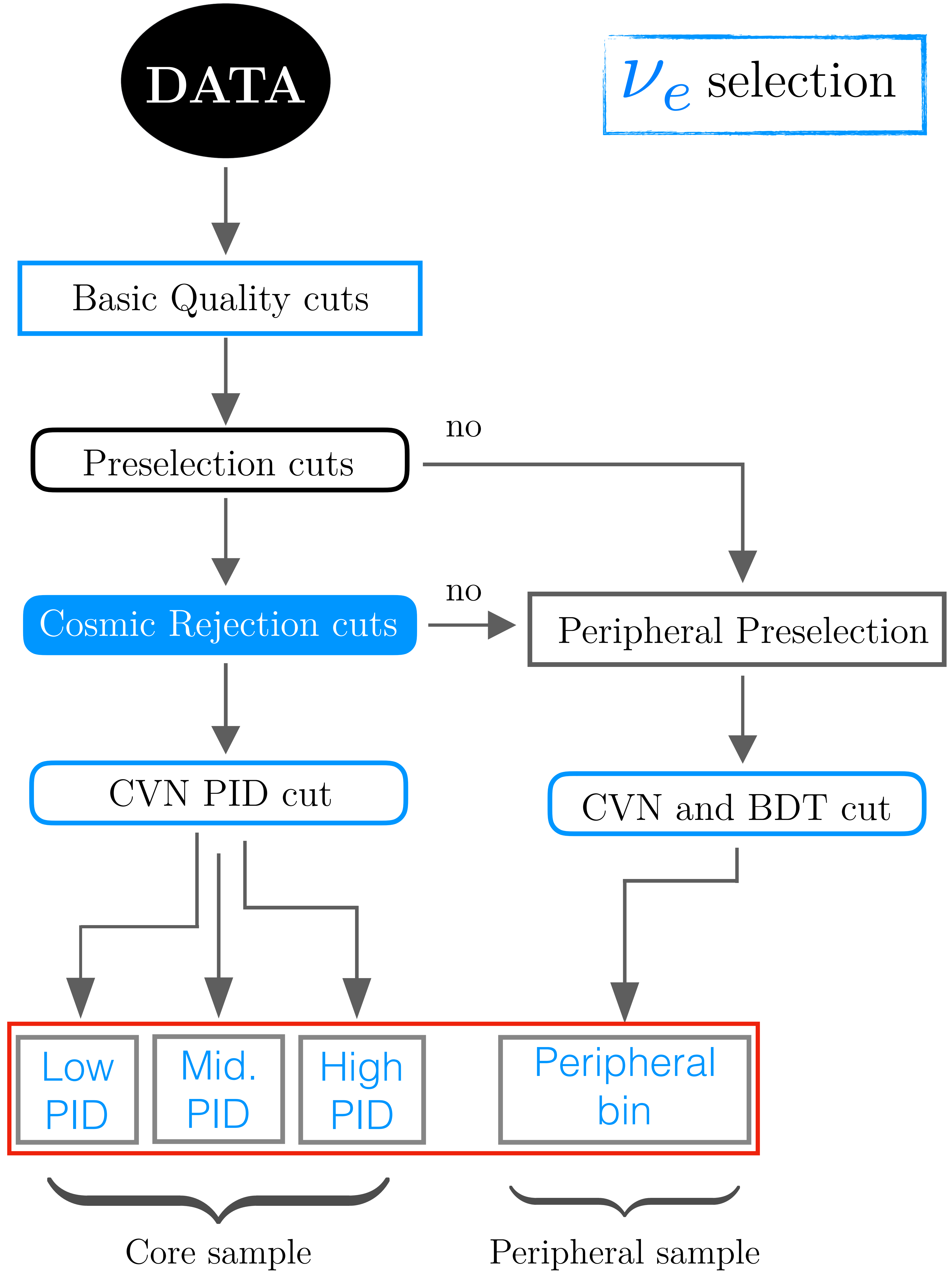
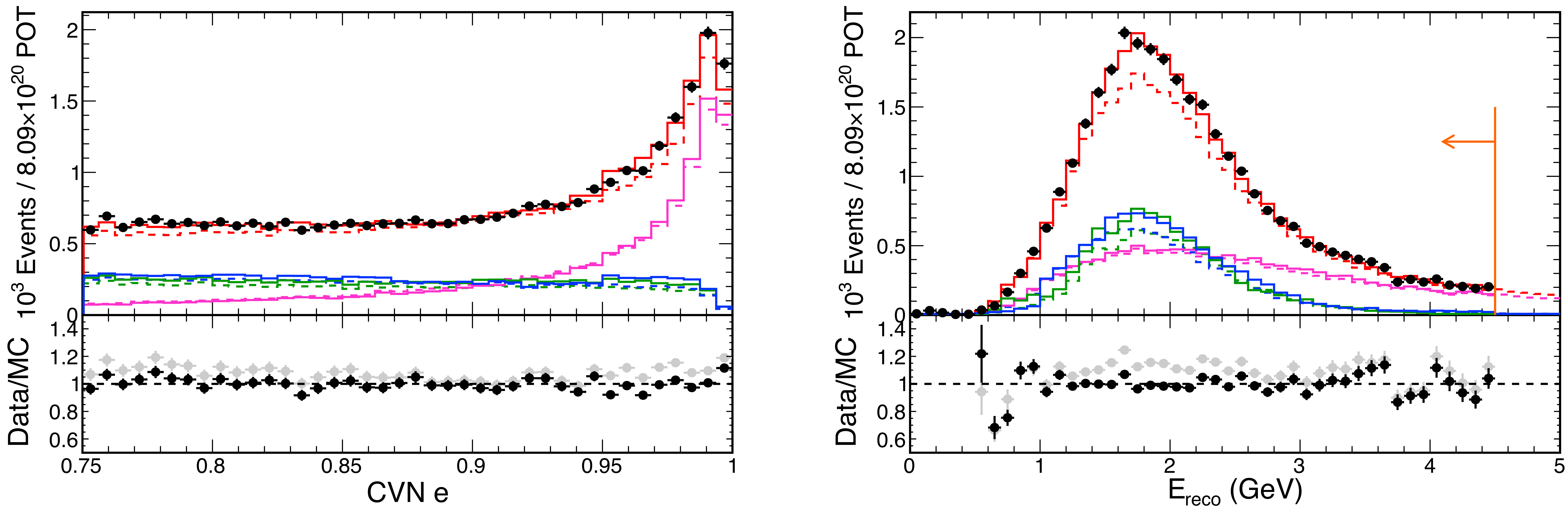




ν_e ND Selected Sample

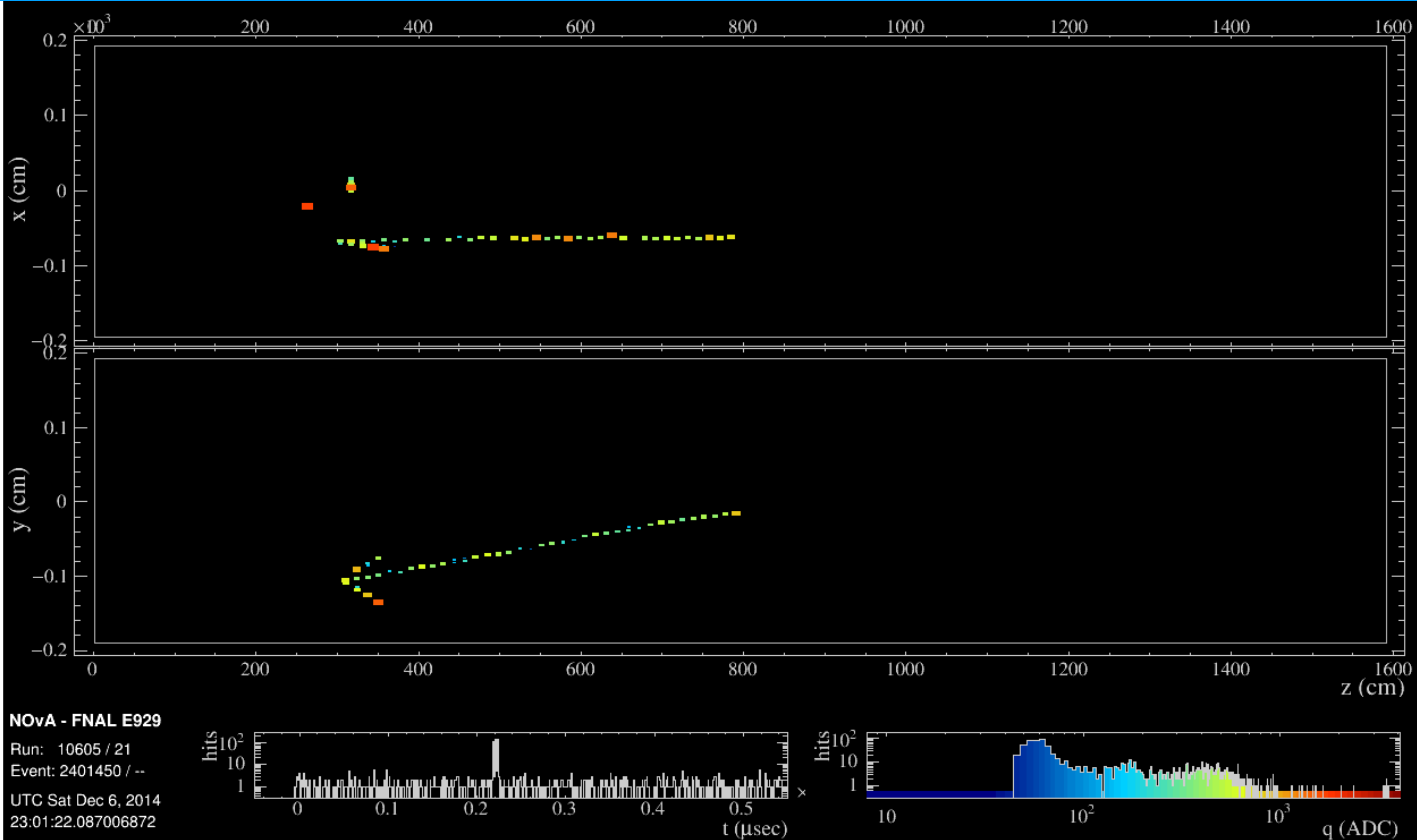
- Signal prediction from the ND selected ν_μ spectra used in disappearance analysis.
- Background prediction from ND selected ν_e data, data driven breakdown of the sample in order to extrapolate each component separately.
- Final background correction: beam ν_e up by 1%, NC up by 20%, ν_μ CC up by 10%.



Muon Removed Electron Added Sample

How to check our performance on our signal sample using the Near Detector?

Try faking appeared electron neutrinos by creating hybrid data/simulation events.



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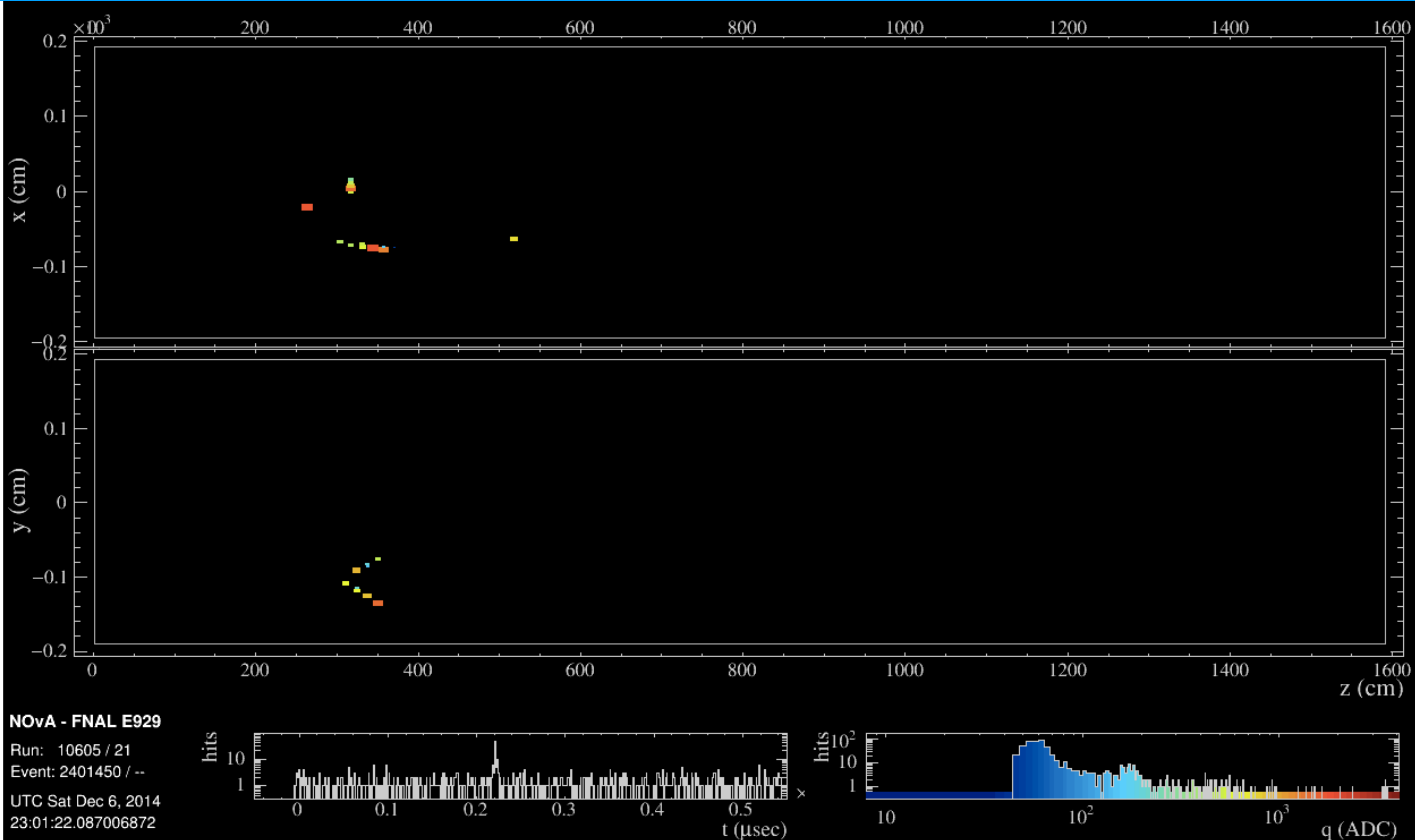

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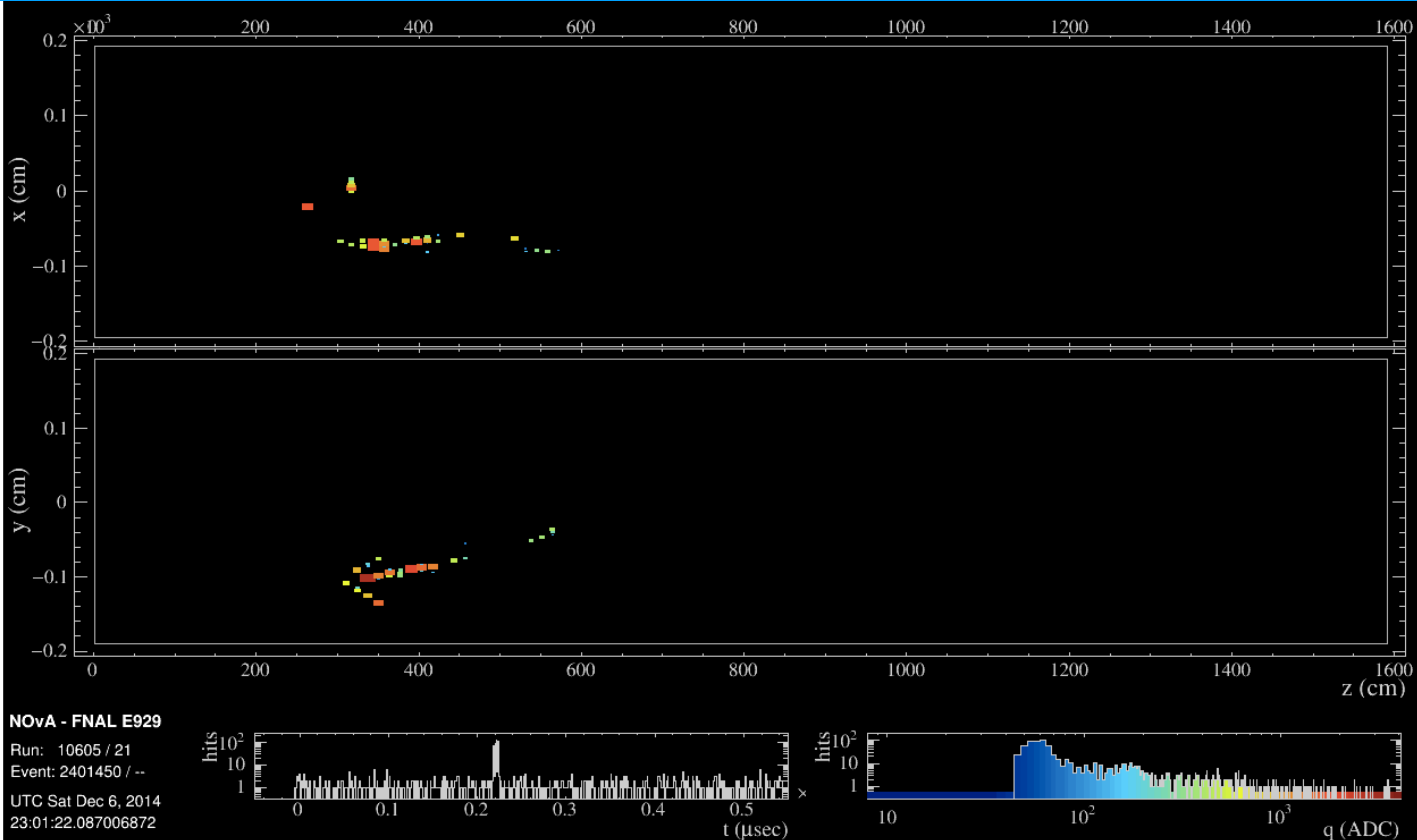
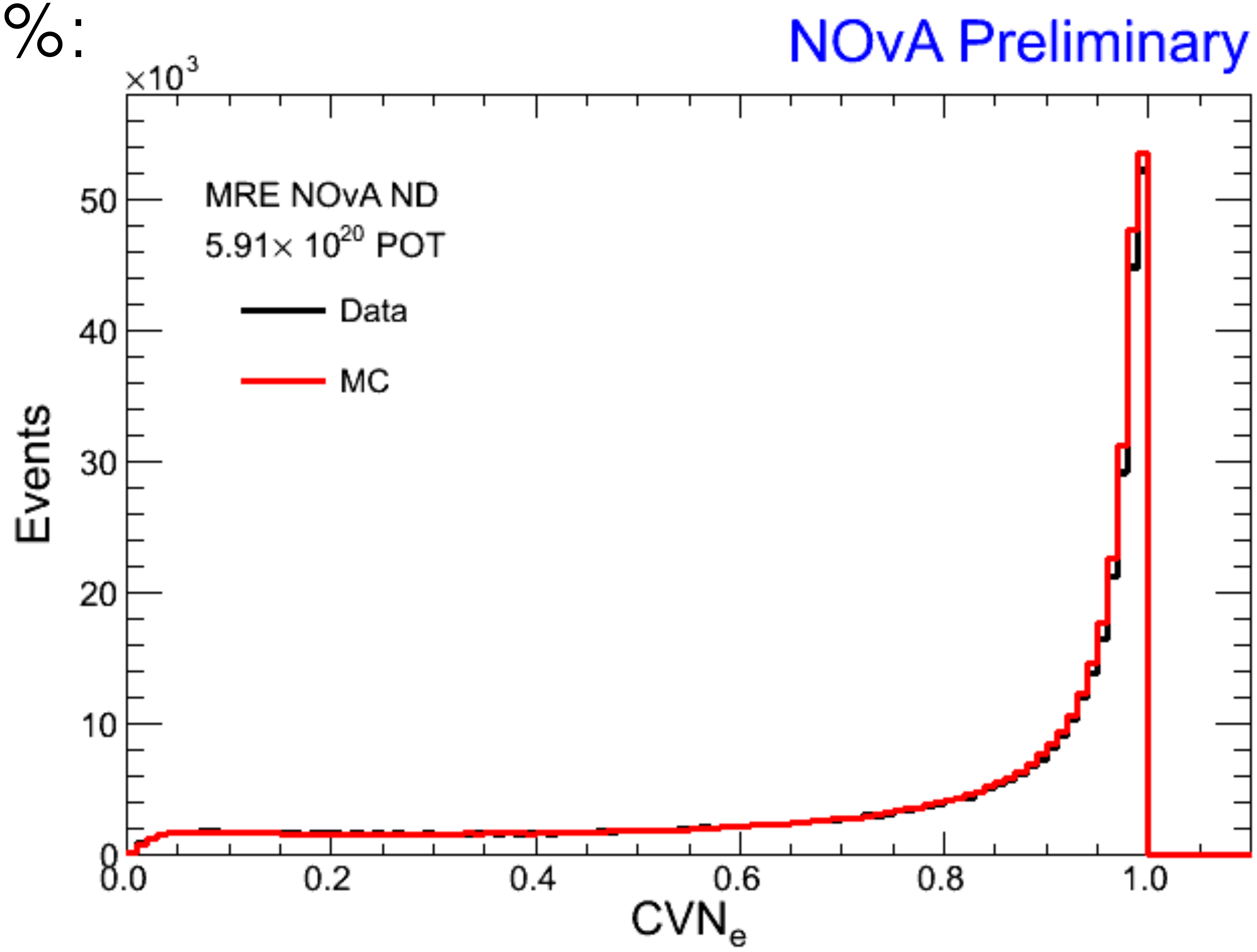


Muon Removed Electron Added Sample

Excellent data/MC agreement in MRE sample. Efficiency difference <2%:



ν_e Systematics

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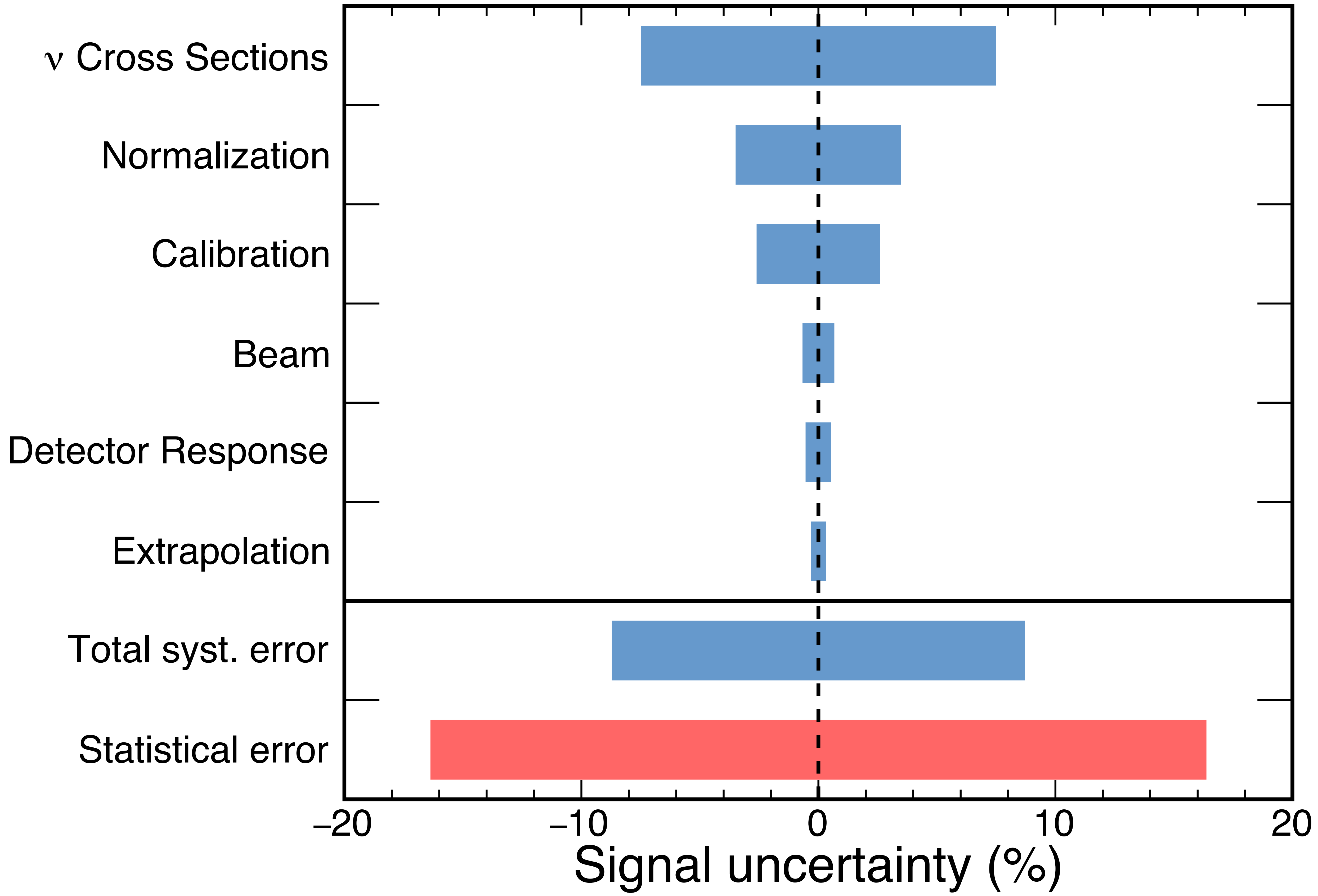
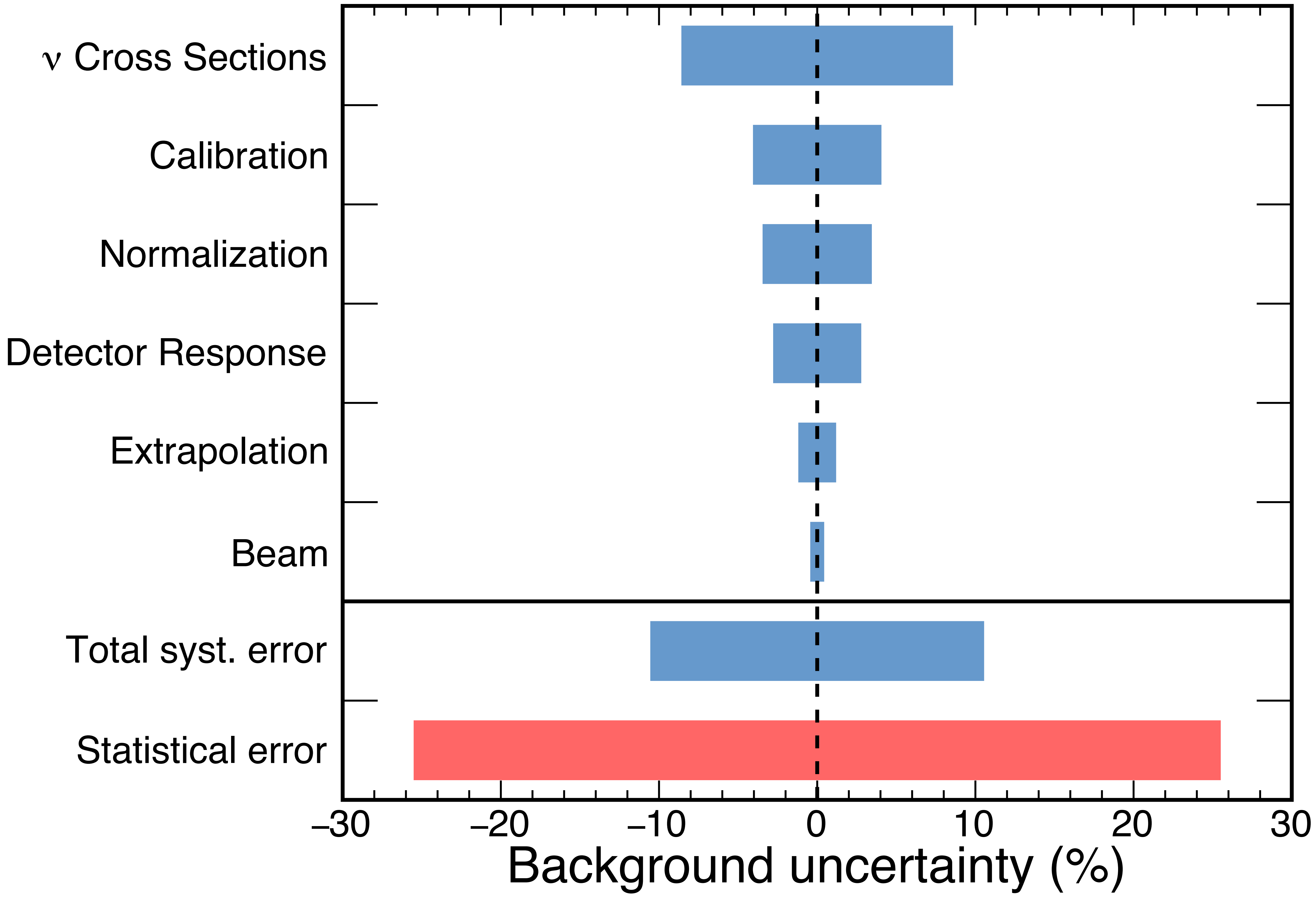
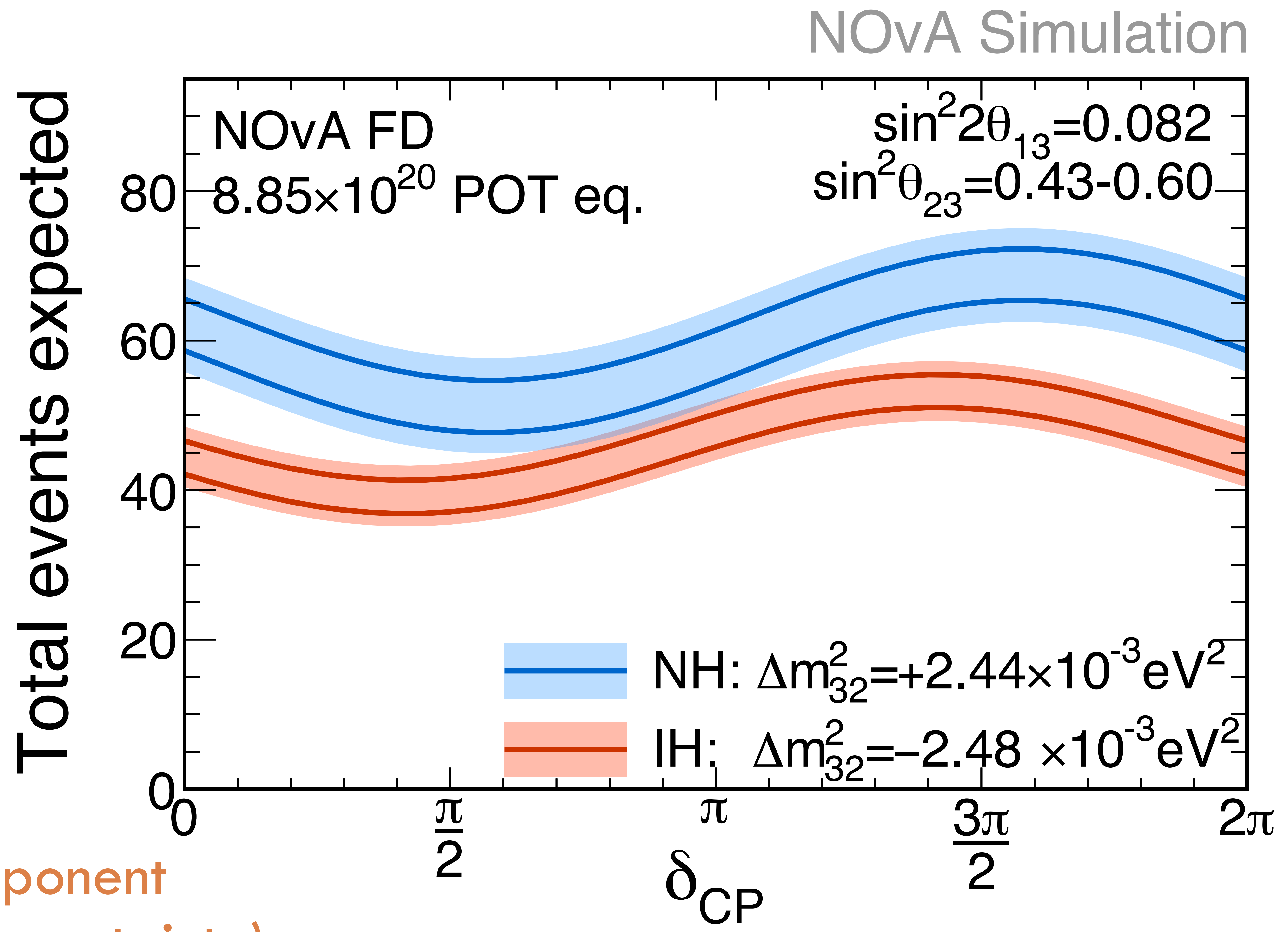
- Those shifted datasets were used instead of our nominal MC to assess the impact on our final result.





ν_e FD Predicted Sample

- Extrapolate each component in bins of energy and CVN output.
- Expected event counts depend on oscillation parameters.



Signal events (±9% systematic uncertainty):

NH, $3\pi/2$,	IH, $\pi/2$,
48	20

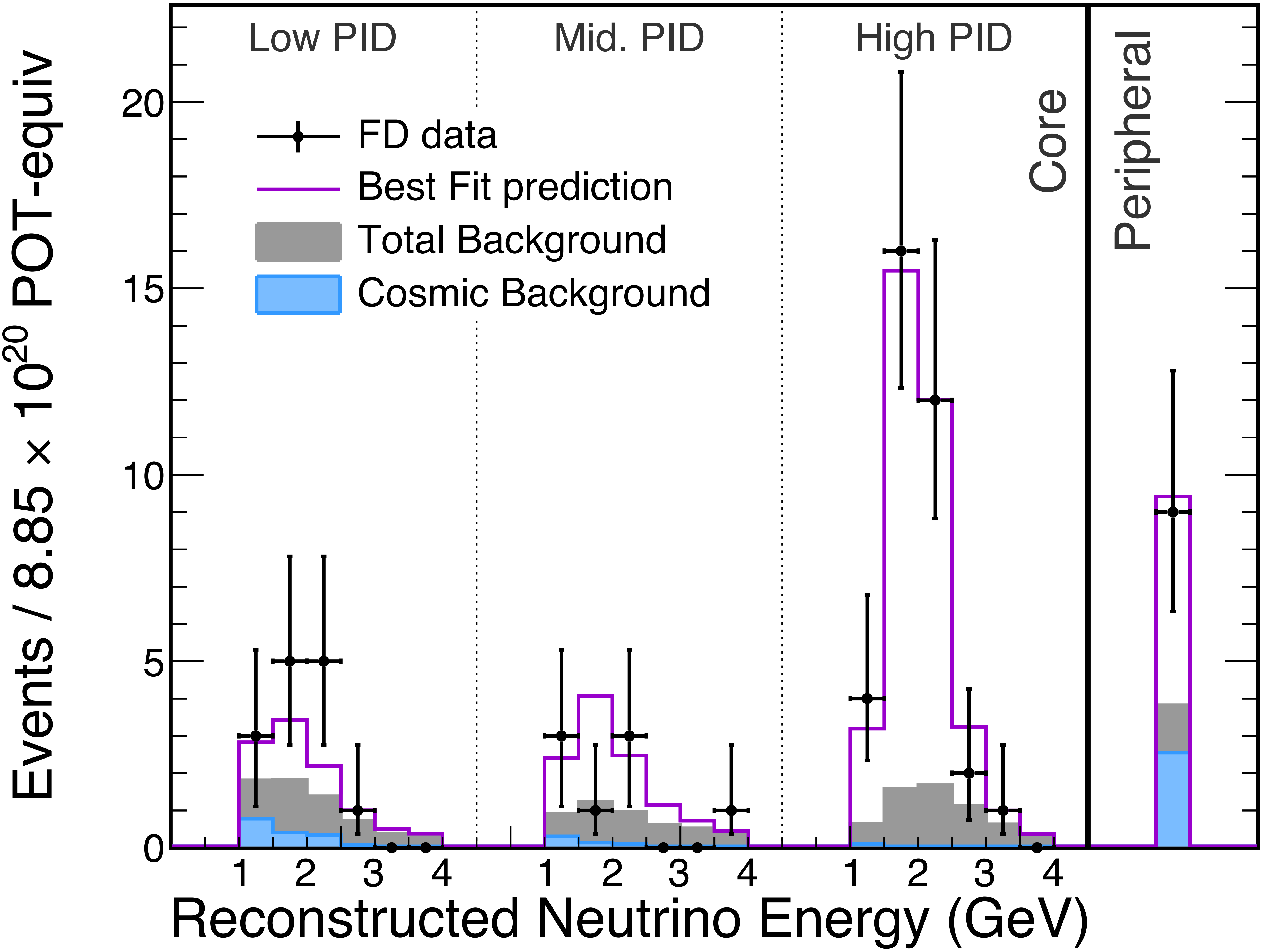
Background by component (±10% systematic uncertainty):

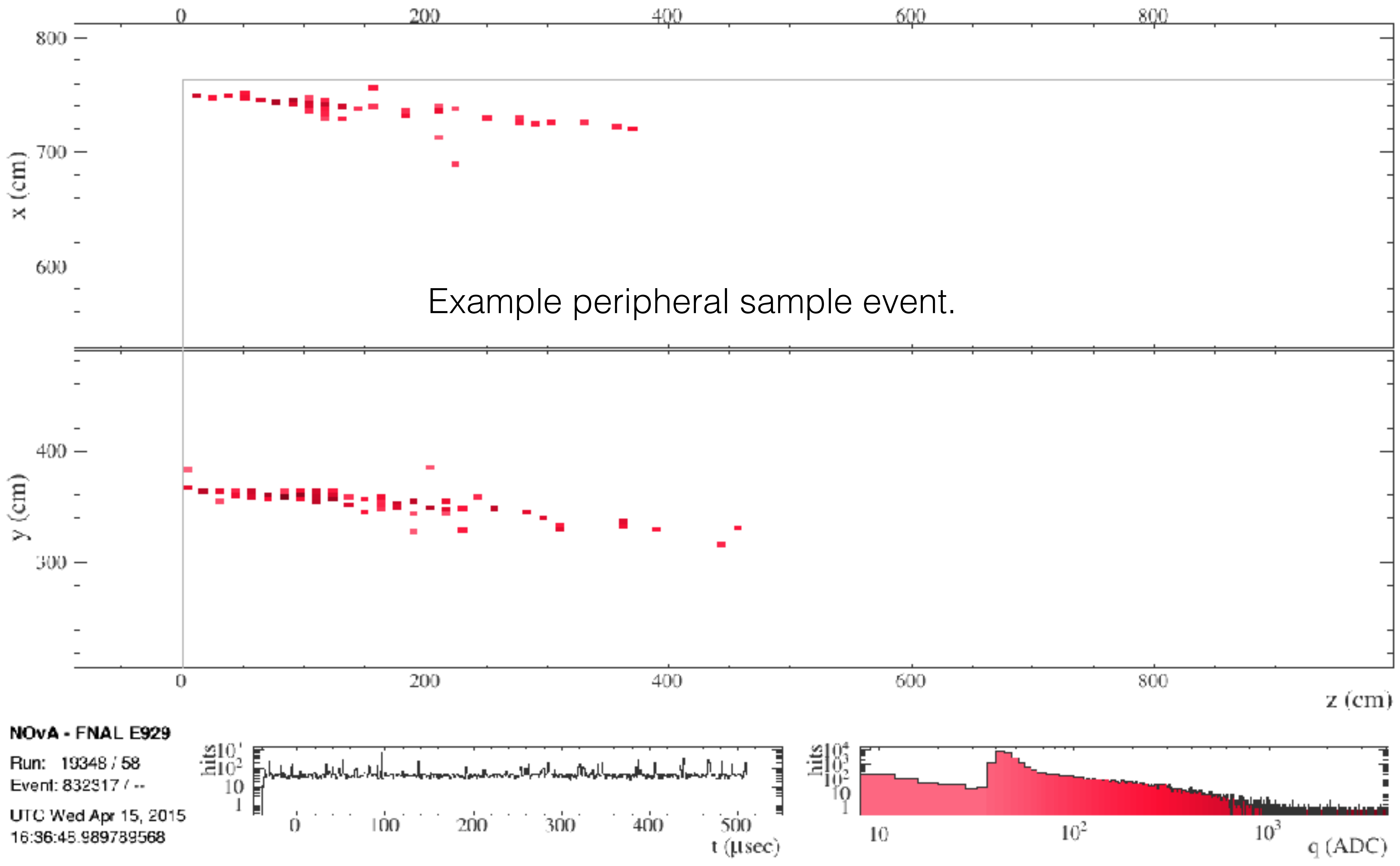
Total BG	NC	Beam ν_e	ν_μ CC	ν_τ CC	Cosmics
20.5	6.6	7.1	1.1	0.3	4.9

ν_e FD Selected Sample

Observe **66 events in FD**. Background Expectation 20.5±2.5.

NOvA Preliminary





Joint Best Fits

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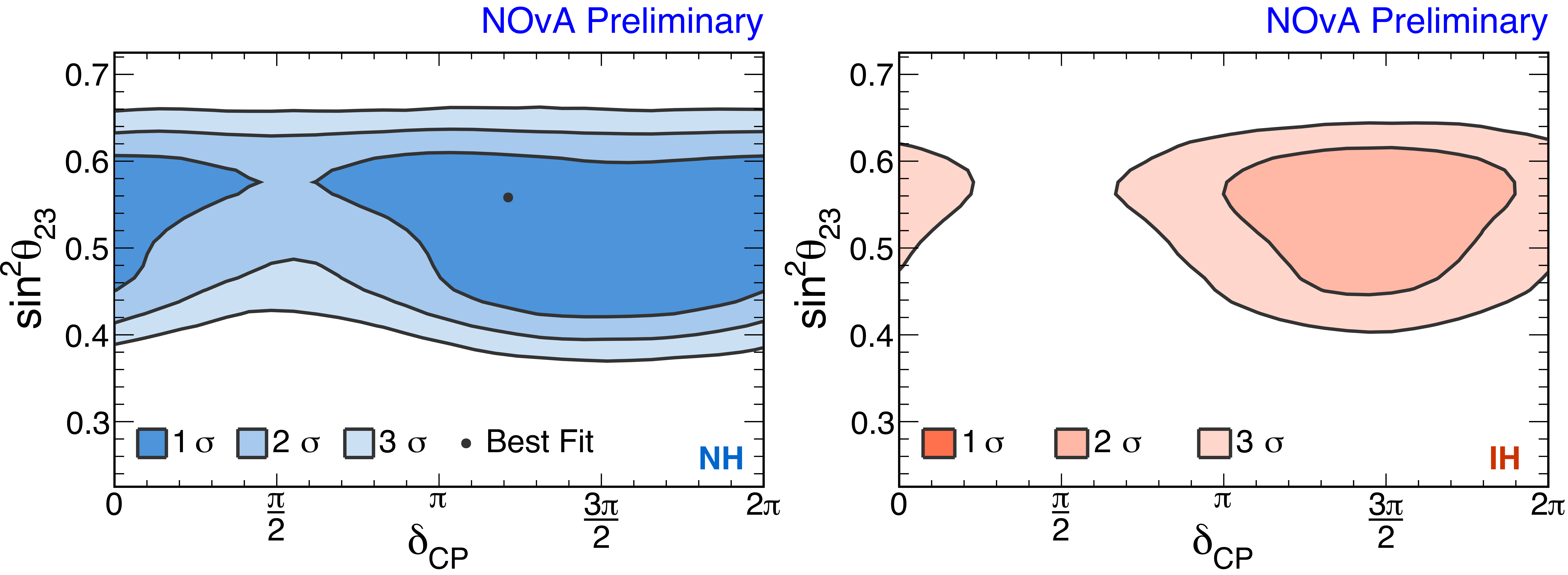
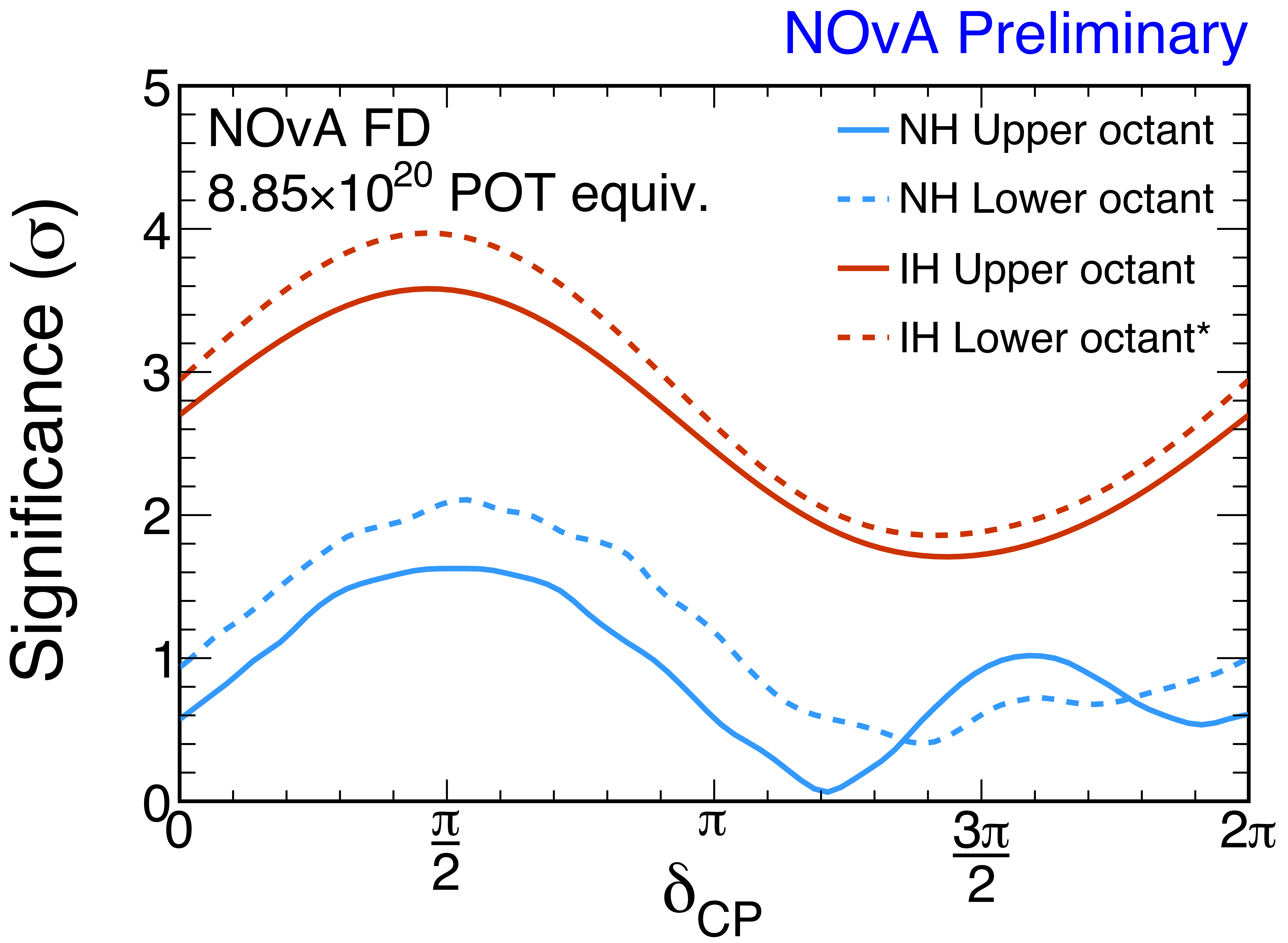


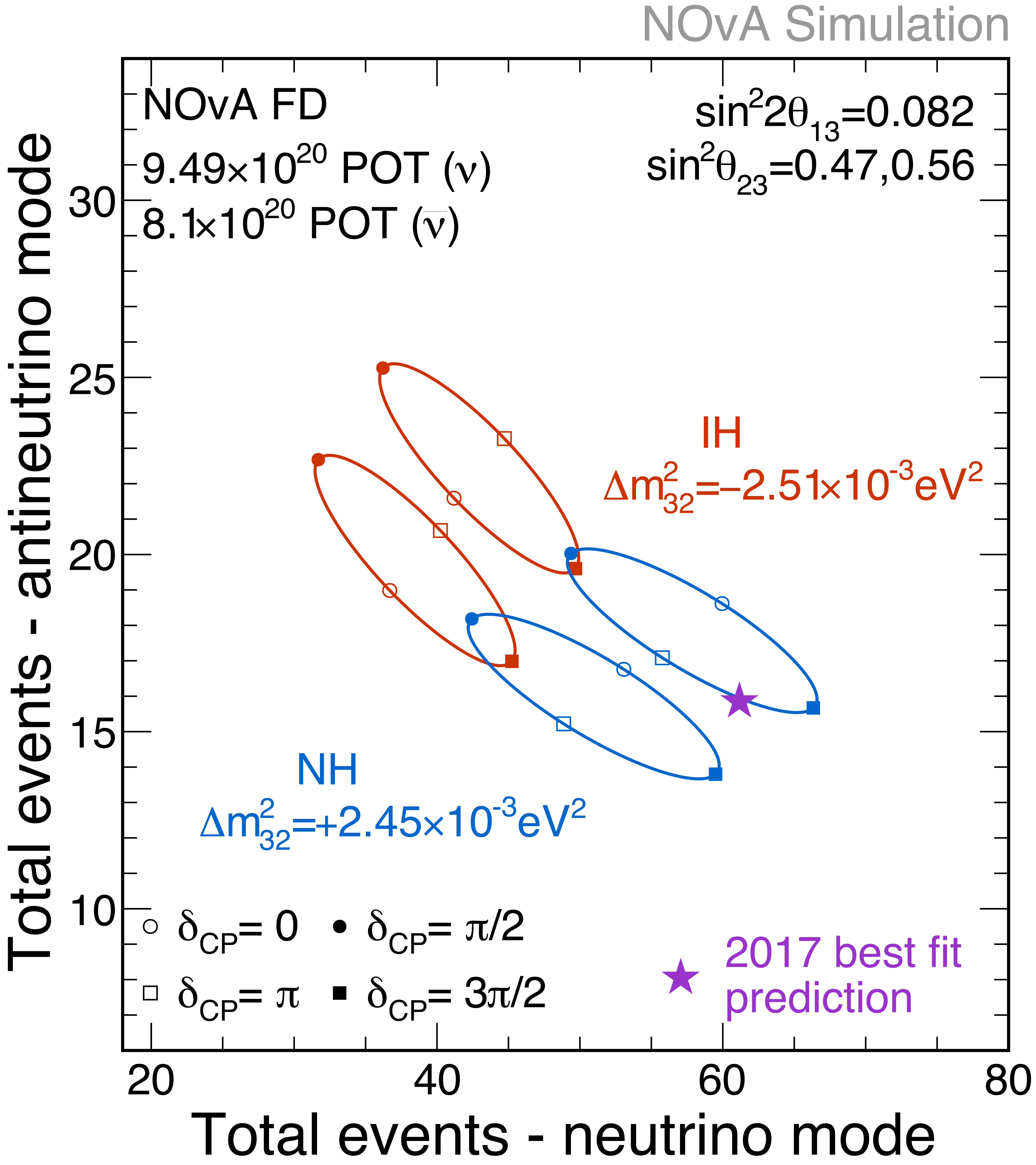
Joint Best Fits

IH at $\delta_{cp} = \pi/2$ disfavored at greater than 3σ.

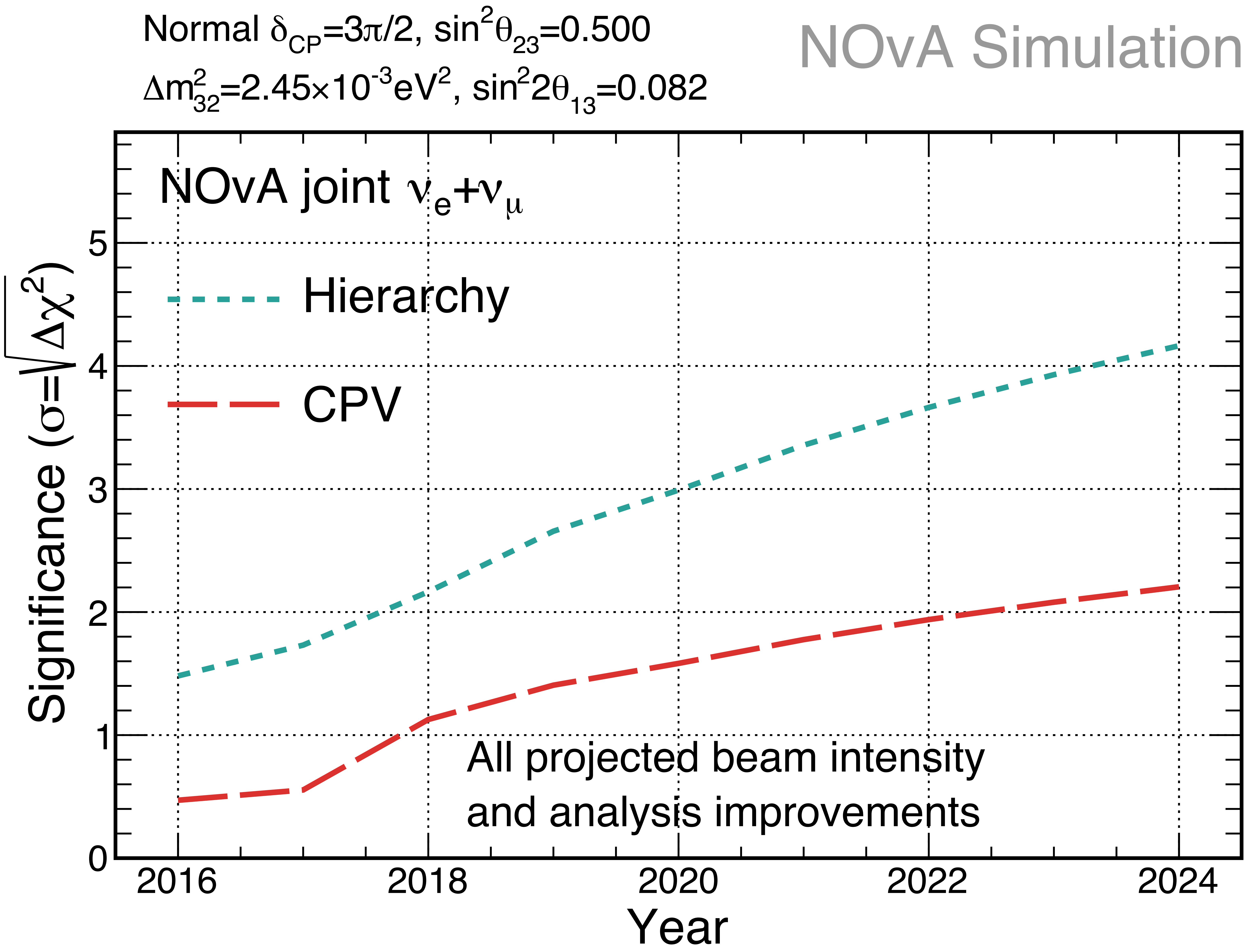
Approaching IH rejection at 2σ.



The Future


NOvA Simulation
NOvA FD
9.49×10^{20} POT (ν)
8.1×10^{20} POT ($\bar{\nu}$)
$\sin^2 2\theta_{13}=0.082$
$\sin^2\theta_{23}=0.47,0.56$
IH
$\Delta m^2_{32}=-2.51\times10^{-3}\mathrm{eV}^2$
NH
$\Delta m^2_{32}=+2.45\times10^{-3}\mathrm{eV}^2$
$\delta_{CP}=0$
$\delta_{CP}=\pi/2$
$\delta_{CP}=\pi$
$\delta_{CP}=3\pi/2$
2017 best fit prediction
Total events - antineutrino mode
Total events - neutrino mode
10
15
20
25
30
20
40
60
80

The Future


Normal $\delta_{CP}=3\pi/2$, $\sin^2\theta_{23}=0.500$
$\Delta m^2_{32}=2.45\times10^{-3}\mathrm{eV}^2$, $\sin^2 2\theta_{13}=0.082$
NOvA Simulation
NOvA joint $\nu_e+\nu_\mu$
Hierarchy
CPV
All projected beam intensity
and analysis improvements
Significance $(\sigma=\sqrt{\Delta\chi^2})$
Year
0
1
2
3
4
5
2016
2018
2020
2022
2024

Conclusions

- At 8.85×10^{20} POT, NOvA finds:
  - **Muon neutrinos disappear:** Competitive measurement of Δm^2_{32}, new analysis prefers mixing near-maximal.
  - **Electron neutrinos appear:** Inverted Hierarchy at $\delta_{cp} = \pi/2$ disfavored at greater than 3σ. Approaching 2σ IH rejection.
- **Excellent detector and beam performance.**
- **Significant improvement in our analysis tools.** Expected to continue, benefiting from efforts like the NOvA test beam.
- Looking forward to opening the box on our first antineutrino data this summer! Expect NOvA to continue to contribute to key questions:
  - Is δ_{cp} nonzero?
  - What is the mass hierarchy?

Many thanks from the NOvA collaboration to the DOE and to Fermilab National Accelerator Laboratory. Thanks to the NSF for my own funding.